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On the estimation of prediction accuracy in numerical offshore pile driving noise modelling

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ABSTRACT

Due to the massive, worldwide increase in the number of constructed offshore wind farms, the ecological impact of construction sites has become an important issue. Hereby, the topic of sound radiation from the needed pile driving procedures for the pile foundations of the turbines has gained a lot of attention lately. Therefore, several numerical models are currently developed to accurately predict sound pressure levels (SPLs) in several kilometers distance to the pile. The topic of parameter uncertainties, being important for every numerical model, is of special significance for these predictions. The extremely large dimensions of the domain of interest and the difficulties in determining, for example the bottom parameters, inevitably lead to a significant degree of uncertainty for the input parameters of the model. In this contribution, a coupled finite element/wavenumber integration model is presented and validated by measurements. Subsequently, the validated model is used to exemplify the effect of parameter uncertainties on the resulting SPLs in the water column, using Monte Carlo simulations. Hereby, the sensitivity of the model to different input parameters is given, as well as a quantification of the resulting prediction accuracy.

Keywords: Pile driving noise, wavenumber integration, parameter uncertainties, Monte Carlo simulations

I-INCE Classification of Subjects Number(s): 12.2.3, 54.3, 75.1, 76.9

1. INTRODUCTION

The problem of anthropogenic noise in the oceans and its impact on marine wild life has been investigated mainly with a focus on shipping noise and seismic surveys until a few years ago. Recently, due to the massive increase in constructed offshore wind turbines, offshore pile driving noise has gained a lot of attention in this context. On the one hand, the extremely high emitted sound pressure levels (SPLs) are comparable to those known from airguns. On the other hand, the numerous piles that have been and will be driven, each requiring a couple of thousand strikes, resemble more to a permanent sound source, as for example shipping noise. Thereby, pile driving noise combines the negative acoustic effects on the environment of high SPLs and long periods of exposure.

The possible negative effects on the marine environment, especially on marine mammals, are currently under investigation, see for example Bailey et al. (1) or Kastelein et al. (2). For an environmental impact assessment, both the physical consequences, such as temporary or permanent threshold shifts, as well as secondary effects such as temporarily habitat loss are of major importance.

To estimate the effects of planned wind farms and to optimize possible sound mitigation systems, numerical modelling techniques play a major role, as simple decay laws have proven to be highly inaccurate for this application, though still widely used. Therefore, different modelling approaches have been developed to predict SPLs from offshore pile driving noise. In this contribution, the prediction accuracy of these models is discussed focusing on the far field, with respect to different sources of uncertainties. In section 2 a brief overview of different numerical modelling approaches is given. The main factors influencing the prediction accuracy are discussed in section 3, and their quantitative effect is evaluated wherever possible. Subsequently, an example of incorporating these factors into a numerical model, using the Monte-Carlo method is presented in section 4, before summing up the results and giving an outlook on future tasks in section 5.

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2. NUMERICAL PREDICTION OF PILE DRIVING NOISE

The task of numerical pile driving noise prediction is mainly complicated by two opposing factors. On the one hand, SPLs are needed in large distances to the pile to estimate their effect. Marine mammals, on the other hand, can sense signals up to the high kHz regime, leading to very short wavelengths. The second point can be addressed by only accounting for frequencies up to 2 or 3 kHz, as measurements show that no significant energy is emitted above this threshold. However, a standard global modelling approach, for example by means of finite element (FE) computations is still unfeasible due to computational restrictions, even for this constrained frequency range.

To address this problem, different hybrid approaches have been developed, splitting the problem into a near field model, accurately modelling the pile vibrations and its close environment, and a far field model, using a standard underwater acoustic propagation method. Examples for these hybrid modelling approaches can for example be found in Stokes et al. (3), Reinhall and Dahl (4) or Zampolli et al. (5). The model suggested in this contribution is a hybrid FE/wavenumber integration approach, using a point source array for the coupling between the two sub-models. For more information on the latter model, the reader is referred to Lippert and von Estorff (6) and Lippert and Lippert (7).

The recently held COMPILE workshop (8) on the numerical prediction of pile driving noise showed that different existing modelling approaches yield remarkably comparable results. The deviations for ranges up to several kilometers were as low as a few decibels, for a basic, generic test case which was prescribed very detailed. This hints to the fact that several good models are available by now, for the needed predictions.

The question remains how accurate the predictions of these models are for realistic, complex environments, including a lot of factors which are as difficult to measure as to account for in the model. However, the quantification of this accuracy is crucial for a well founded prediction.

3. INFLUENCING FACTORS ON PREDICTION ACCURACY

There are numerous factors influencing the prediction accuracy of a numerical model which, in general, can be classified into three different groups, each being addressed in the following. The first part deals with the simplifications involved in the chosen modelling technique, the second part looks at the quality of the needed input parameters, whereas the third point discusses the accuracy of the measurement data used to validate the model output.

3.1 Modelling simplifications

Every model only represents a simplification of the real world, focusing on the most important factors for the problem under consideration to efficiently give a reasonable result. The crucial question is which factors are considered important and which can be neglected. For example, a linear fit to a quadratic curve will only give reasonable results in an extremely limited parameter space. Then again, a fit using a polynomial order of ten would give highly accurate results, while consuming far more resources than needed.

As most modelling approaches for the problem at hand, a propagation method is used for the modelling of SPLs over long ranges. These models represent a trade off between accuracy and computational effort. The chosen wavenumber integration approach, based on Schmidt and Tango (9) has the advantage of representing the full field, including for example ground roll waves and the full evanescent spectrum. Also, an arbitrarily layered structure consisting of fluid and elastic layers can be modeled. Its biggest draw back is the inherent assumption of range independence, i.e. all layers are assumed to be infinite and flat. However, for the application the model was designed for, i.e. SPL predictions in mid-ranges of up to 5 km in the relatively flat of the North Sea, no significant changes of the bathymetry are expected.

In the absence of strong bathymetry changes, the most influential simplifications are estimated to be the roughness of the sea surface and the bottom interfaces, as well as the representation of the bottom either as an elastic or equivalent fluid medium. To take care of the first point, a modified reflection coefficient instead of a classic pressure release boundary condition can be used at the air-water interface. To account for additional damping effects from water wave-induced surface bubbles, a modified upper fluid layer can inserted, see for example Ainslie (10). However, an implementation of this approach to the described WI model only showed significant effects either for frequencies way above the considered upper limit, or for distances above 10 km. A reason for this is the restriction of most offshore construction activities to to maximum significant wave height of about 2 m, which guarantees for a relatively smooth surface.

The biggest source of uncertainty poses the modelling of the bottom, being an inhomogeneous multi-phased water-sand mixture, which can for example be described on the basis of the Biot theory, see Biot (11). For most of the underwater acoustic propagation approaches however, the bottom is either represented as a linear-elastic or fluid material, see Jensen et al. (12). The quantification of the resulting error, especially between the elastic and the fluid approximation, is difficult to generalize and is currently under investigation by the authors.

3.2 Input parameters

The question of the accuracy of the input parameters is important in all fields of numerical modelling, but of special interest for the case of pile driving noise predictions. This mainly results from the vast size of the domain of interest and the difficulties of obtaining precise measurement data under offshore conditions, as well as time varying effects on different time scales.

One classic example for this is the profile of the sea surface on a scale of several kilometers. A deterministic description of this profile is not feasible for every recorded pile driving strike during a measurement campaign. Therefore, in most cases the significant wave height is measured which can, in combination with a suitable wave spectrum, be used to determine an average surface roughness loss as input parameter for a numerical model, see for example Ainslie (10).

Another example would be the sound speed profile in the water column which can vary rapidly with time, either around a relatively constant base profile or leading to sound channels, especially in the Baltic Sea, see for example Etter (13). The profile can easily be measured using a CTD (conductivity, temperature, depth) sensor, but again, a simultaneous measurement at all depths for all strikes is rather unfeasible.

Apart from the two described problems, originating from strongly time-dependent processes, the characterization of the bottom and its layered structure is an important point when it comes to the problem at hand. For shallow water environments, the interaction of the sound field is in most cases dominantly characterized by interactions with the soil. In addition, in the case of pile driving acoustics, part of the source is buried in the ground, making the bottom parameters more important than in the case for airgun simulations, for example.

However, the characterization of the soil, for example by seismic inversion, is always afflicted with a significant degree of uncertainty, both in the determination of the layered structure itself, i.e. the layer depths Δz, and the parameters of the single layers, i.e. the sound speed c_p, the density ρ, and the damping factor δ. The accuracy of the parameters estimations, normally given in the form of normal distributions, i.e. mean value μ and standard deviation σ, varies for the different parameters as well as between each single measurement, depending on the environmental conditions. For example, in Wilken and Rabbel (14), the standard deviation of an inversion algorithm for the shear speed in different bottom layers was found to be about 10% of its mean value, for that particular case.

3.3 Validation data

To estimate the accuracy of a numerical model the validation process, i.e. the comparison to actual measured data, is essential. In this context, the accuracy of the validation data is of course of utmost importance. For the measurement of pile driving noise by hydrophones, the actual accuracy of the SPL and the position of the hydrophone are decisive.

The authors took part in the planning and execution of three major offshore measurement campaigns in the North Sea, each involving dozens of hydrophones. In the evaluation of the data, the degree of variation between nominally similar strikes was often observed to be at least around $2-3\,\mathrm{dB}$. The order of magnitude of $3\,\mathrm{dB}$ for the measurement uncertainty is commonly used for the measurement of pile driving noise, though hard to find as a published reference. The reasons for these variations can probably be found in time varying factors, such as the instant profile of the sea surface and sound speed profile, as already mentioned. Another reason might be the relation to the actual position of the hydrophone, as discussed below.

The inaccuracy with respect to the actual measurement position is mainly caused by four different factors, i.e. the inaccuracy of the Global Positioning System (GPS) itself, the position of the GPS antenna in relation to the point of deployment on the ship, the drift of the system on its way from the sea surface to the floor and the tilting of the hydrophone system in the current.

The GPS signal itself is rather exact, providing positioning data with an accuracy of about 1 to 3 m, for most modern systems.

The biggest problem is the position of the GPS antenna, which normally is located above the bridge, while the hydrophone systems are deployed at the fore or the aft of the ship. As a standard procedure, the GPS coordinates are locked at the moment of deployment, but, depending on the size and the layout of the ship, normally deviate between 20 and 50 m from the actual point of deployment. However, this information is often unavailable at the time of the validation. In figure 1a, this is exemplified by a sketch of one of the research vessels used for one of the mentioned offshore measurement campaigns, having a distance deviation of about 30 m between the nominal and actual position of the point of deployment.

As standard hydrophone systems are relatively heavy and slender, the drift while sinking to the sea floor is estimated to be negligible in most situations, as long as the deployment vessel is at halt.

The last important factor is the position of the hydrophone itself within the measurement system, as depicted in figure 1b. To compensate for the tidal range and waves, as well as for recovery purposes, the line between the anchor weight and the floating buoy is about $1.5-2$ times the average water depth. In the presence of currents, this leads to a drift of the buoy and a tilting of the line. The actual displacement of the hydrophone with depth and range depends on its original positions. As an example, at the measurement campaigns mentioned above and used subsequently for the validation, hydrophones were installed in nominal depths of 2 and 10 m above the seafloor. This may lead to a displacement of the ladder position of $\Delta r = 7-9\,\text{m}$ and $\Delta z = 3-5\,\text{m}$, respectively.

Summing up these spatial uncertainties, the total uncertainty in range can be estimated to be around $\Delta r_{total} \approx \pm 30 - 60\,\text{m}$ and that in depth to be $\Delta z \approx \pm 3 - 5\,\text{m}$, which poses a significant problem to a precise model validation.

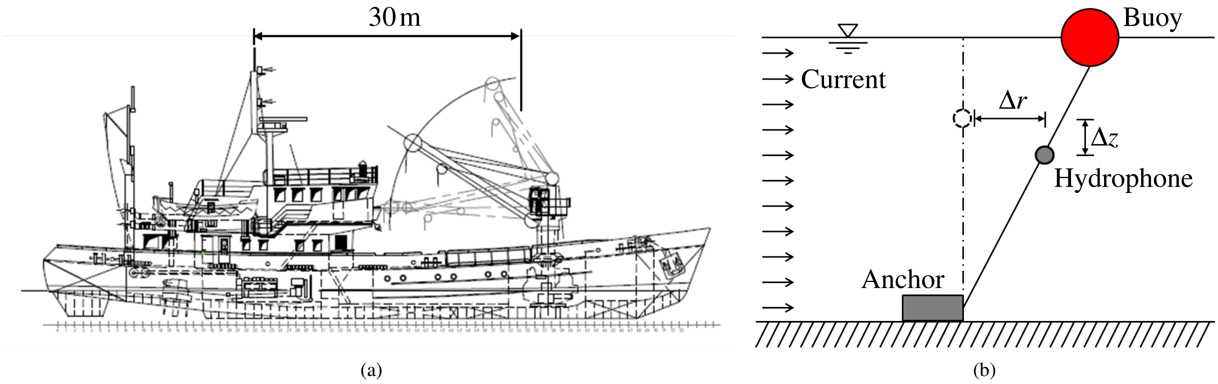
It is estimated that the measurement uncertainty of $2-3\,\text{dB}$ is probably strongly interdependent with this spatial uncertainty. Nominally, assuming a smooth logarithmic decay with range as it is often done, even a variation of ±60 m in range would not make much of a difference on the dB-scale. However, recent modelling results show a significant oscillation for both the sound exposure level (SEL), defined as,

$$SEL = 10\log\left(\frac{1}{T_0}\int_{T_1}^{T_2}\frac{p(t)^2}{p_0^2}dt\right), \tag{1}$$

and the peak sound pressure level (SPL$_{peak}$), defined as,

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

around a generally decaying trend, see Lippert et al. (15), with $T_0 = 1\,\text{s}$, the sound event being fully enclosed by the interval boundaries T_1 and T_2 and a reference pressure of $p_0 = 1\,\mu\text{Pa}$. This oscillation could by now be confirmed by measurement data and can also be observed in figure 2b. The cause of this oscillation is believed to be the interference pattern of the broadband source in the waveguide, closely related to the waveguide invariant. The local variation of the SPL$_{peak}$ is more pronounced than that of the SEL, compare figure 2b, as the interference pattern are partly smoothed by the integration in equation 1. This can explain the deviation of several decibels for positions that should normally exhibit similar SPLs, a deviation by a few meters might make the difference between a minimum and a maximum. In addition to that, the displacement of the hydrophone towards the sea bed by the current also has a significant effect, as the sound pressure is known to rapidly increase near the water-soil interface.



(a) (b)

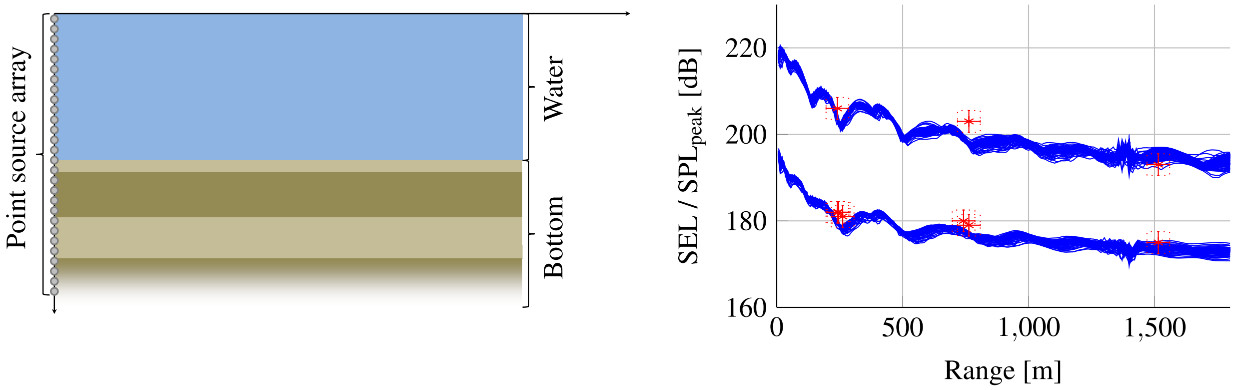
Figure 1 – (a) Sketch of one of the ships used to deploy the hydrophone systems. Indicated length between the GPS antenna and the approximate point of deployment (b) Sketch of the hydrophone displacement due to currents (dashed line indicate nominal position)

4. NUMERICAL INCORPORATION OF UNCERTAINTIES

To account for the factors which influence the prediction accuracy, discussed in section 3, into the model, introduced in section 2, the Monte-Carlo Method is used. Thereby, the influence of the uncertain input parameters on the resulting SPLs is quantified. Subsequently, a validation is performed taking the results from the accuracy analysis of the measurement data into account. Also, the possible effect of the mentioned modelling uncertainties is discussed.

As validation example, measurements during the installation of an unmitigated pile at the BARD Offshore 1 wind farm in the German North Sea is used. The initial soil profile for the far field model is taken from a seismic survey provided by the wind farm constructor, see figure 2a.

The approach to incorporate the input parameter uncertainties into the model is based on the Monte-Carlo method, using a Latin-Hypercube sampling for improved convergence. To exemplify the effect, only the bottom parameters are assumed to be varying, as they are estimated to be the dominating factor. As a first step, all bottom layers are assumed to be fluid media. The parameters of each single layer, i.e. the sound speed c_p, the density ρ, the damping factor δ and the layer thickness Δz, are randomly varied $\pm 10\,\%$ of their nominal value, assuming a Gaussian distribution. Converging results could be achieved after 120 simulations using a coupled finite element/wavenumber integration approach, introduced in section 2 and described in Lippert and von Estorff (7), see figure 2b.



(a) (b)

Figure 2 – (a) Schematic sketch of the far field model setup with layered soil structure (b) Comparison of far field Monte-Carlo simulation (for the bottom parameters) with measurement data (upper group of curves representing the SPL$_{peak}$ and the lower group representing the SEL / error bars indicating the uncertainties of the levels and the actual position)

In accordance with the discussion of the measurement uncertainties both in level and range in section 3, error bars have been added to the measurements. The uncertainty in range for the present example has been estimated to be $\Delta r \approx 45\,\text{m}$ and the uncertainty for both the SEL and SPL$_{peak}$ was chosen to $\Delta SPL \approx 2.5\,\text{dB}$.

Due to a lack of founded knowledge about the order of magnitude of the modelling uncertainty, it will not be considered in the following. However, once the mentioned quantification has been finished, it can easily be incorporated by adding error bars to the single runs of the Monte-Carlo simulation.

Looking at figure 2b, the measurement and Monte-Carlo simulation are in good accordance. The incorporation of the uncertain bottom parameters by the MC simulation leads to a prediction interval of about SEL$_{min-max} \approx 2-3\,\text{dB}$ and SPL$_{min-max} \approx 3-4\,\text{dB}$, with a rising tendency interval at longer ranges.

The comparison of the simulation with nominal bottom parameters to the measurement data (without error bounds), showed a deviation of only as much as 2 dB for the SEL and 4 dB for the SPL$_{peak}$. Comparing the MC simulation to the measurements incorporating the uncertainties, all measurements coincide with the simulations.

It has to be stressed that this is not to say, that the model used at hand is precisely predicting the actual sound pressure levels. Merely, it exemplifies that the standard procedure in the evaluation of pile driving noise of stating single values both for measurements and predictions is somewhat misleading and that prediction intervals should be used for future predictions

5. CONCLUSIONS AND OUTLOOK

The effect of different sources of uncertainty on the numerical prediction of pile driving noise and the validation of these models was discussed. The factors playing a key role were identified to be the modelling simplifications of the used method, the uncertainties of the model input parameters and the measurement inaccuracies, both for the recorded levels and position of the hydrophones. The ladder two points were addressed by applying the Monte-Carlo method to a model developed by the authors and comparing it to measurement data with apriori estimated error bounds for the range and the recorded level.

Based on the assumption that only the bottom parameters were afflicted with uncertainty, the predicted intervals within a range of 1800 m around the pile were found to be SEL$_{min,max} \approx 2-3\,\text{dB}$ and SPL$_{min,max} \approx 3-4\,\text{dB}$. The predicted intervals for both quantities overlapped with the intervals for the measurement data at all positions. For comparison, the simulation with nominal bottom parameters showed deviations of 2 dB for the SEL and 4 dB for the SPL_{peak}.

The good agreement merely reflects the large uncertainties in the measurements. For a more precise validation and thereby for improvements of the model, these have to be significantly reduced. First of all, the degree of incertitude in range could be largely reduced by recording the point of deployment of the hydrophones on the ship in relation to the position of the GPS antenna. Also, information about the current during the measurements might be used to determine the approximate tilt of the hydrophone systems. Such a reduction in range inaccuracy would probably lead to a significant reduction of the level uncertainty estimation, as discussed above.

With respect to the input parameter uncertainties it is crucial to get a good estimate for the standard deviation of each parameter in each layer, to correctly account for the uncertainties in the Monte-Carlo simulations. Also, the question of the importance of shear wave components for different sediment types is important and therefore currently under investigation by the authors.

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