Integral approach for modelling offshore bubble curtains

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ABSTRACT

The construction of offshore wind turbine foundations in the North Sea with an impulsive hammer is related to high noise emission. For the protection of the maritime environment, the German government constituted limits of 160 dB in 750 m distance to the pile. To meet the regulations noise mitigation systems are used, especially the bubble curtain. Besides the intensive utilization of the bubble curtain, the main effect of the noise reduction has not been understood. A model of the bubble curtain has been developed which takes the local variation of the physical properties and the impact of the upper soil layers into account. Comparisons with offshore measurements are presented.

Keywords: Bubble Curtain, Noise Mitigation, Offshore-Wind-Energy.
I-INCE Classification of Subjects Number(s): 54.3

1. INTRODUCTION

The offshore wind energy plays an important role in the expansion of the renewable energies in Germany. Many wind turbines are supported by monopiles. During the founding by impact pile driving pressure waves are radiated into the water. High underwater sound exposure levels can be measured in far distance to the pile. Especially the harbour porpoise relies on hearing for its orientation. The intensive noise emissions are a potential threat to the already endangered creature. To protect the maritime environment the German government established a limit of 160 dB as SEL in 750 m distance to the pile. Noise mitigation systems have been developed in the last years to keep those limits. The bubble curtain is an often used system. Although a lot of experience with the handling of the bubble curtain was gained in the last years [e.g. (1), (2)], there is no reliable method to predict the noise reduction for a certain pile and location.

The acoustical properties of a bubble curtain result from the local behaviour of the bubbles. Minnaert (3) proved that bubbles interact with an incident wave as an oscillator. Strong absorption and scattering of the pressure wave can be observed close to the eigenfrequency. Commander and Prosperetti (4) presented an algebraic model to calculate the effective sound velocity of a water-bubble-mixture for a certain ambient pressure and bubble size distribution. The two parameters vary significantly in different depth. The accurate description of an offshore used bubble curtain is therefore only possible with an integral approach considering local effects.

Göttsche et al. (5) modeled a small bubble curtain by combining a Computational Fluid Dynamic simulation with a local bubble acoustic model. The effect of the bubble curtain on the sound propagation has been considered as a reduction of the source strength. A bubble size distribution of an average value of 10 mm and 3 mm standard deviation has been used.

In this paper an integral approach to model the noise mitigation of a big bubble curtain will be presented (i.e. global model of the bubble curtain). A sound propagation model has been setup comprising the water part with the bubble curtain and upper soil layers. A fluid mechanic model of a linear bubble curtain has been combined with a bubble acoustic model to obtain the local effective sound velocity. In the following chapter the integral approach will be presented. First results will be compared with offshore measurements during the construction of the research platform FINO3 in chapter 3.

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2. GLOBAL MODEL OF A BUBBLE CURTAIN

The global model comprises a linear acoustic FE-model in frequency domain and submodels for the definition of the local sound velocities of the soil and the bubble curtain. Figure 1 gives an overview of the axisymmetric computational domain and the boundary conditions. The pile as line source has been replaced by an incoming wave with an amplitude of 1 Pa. This is justified by the far distance between the pile as source and the bubble curtain. The sea surface is handled with the pressure release condition. Perfectly-Match-Layers (PML) are defined on the right side and the lower edge of the domain.

The bottom has been modeled as a fluid using the far-field soil model from Fricke and Rolfes (6). The bubble curtain is represented by the local effective sound velocity. The fluid model of a linear bubble curtain from Ditmars and Cederwall (7) is used to determine the distribution of the air fraction. Considering a normalized bubble size distribution the local bubble size distribution is calculated. The local effective sound velocity is evaluated by the model of Commander and Prosperetti (4).

The transmission loss due to the bubble curtain is specified by the insertion loss in third octave bands according to Müller and Zerbs (8). Following the standard literature the transmission loss is defined as

$$TL_{1/3\ \mathrm{octave}} = SPL - SPL_{\mathrm{ref}} \tag{1}$$

where SPL and $\mathrm{SPL_{ref}}$ are the sound pressure levels with and without the noise mitigation system. The SPL is calculated in accordance to Zampolli et al. (9) by

$$SPL = 10 * \log_{10}\left(\frac{\int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} 2\,|P(f,\boldsymbol{x})|^2 \mathrm{d}f}{1\ \mu\mathrm{Pa}^2\mathrm{s/Hz}}\right) \tag{2}$$

where $P(f,\boldsymbol{x})$ is the Fourier transformation of the local sound pressure. f_{min} and f_{max} denote the lower and upper frequency of the band level. The integral in (2) is approximated by five supporting points for every band level. According to Fricke and Rolfes (6) the mesh is adapted for every band ensuring an efficient calculation of the noise mitigation.

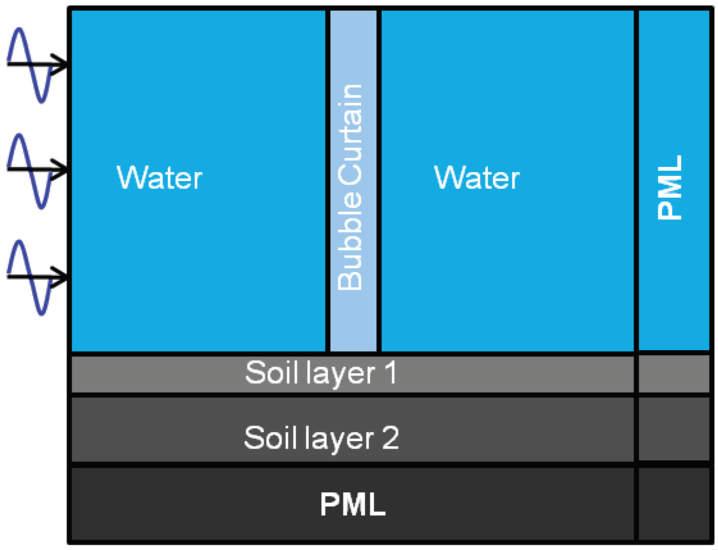

Figure 1 – Computational Domain with boundary conditions

3. COMPARISION WITH MEASUREMENTS AT THE RESEARCH PLATFORM FINO3

3.1 Measurements at FINO3

During the construction of the research platform FINO3 measurements of the sound pressure have been conducted in different distances to the pile. Table 1 lists the considered measurement points close to the pile. The water depth is 23 m at the location of the pile and the average tidal flow velocity was around 0.5 ms^{-1}. A bubble curtain has been placed in 70 m distance provided with an operational air flow of 0.39 $m^3min^{-1}m^{-1}$ during the piling (10).

Table 1 – FINO3: Measurement positions (10)

Parameter	MP 2	MP 3
Distance to the pile in m	245	910
Height above the ground in m	8.0	1.2
Position relative to the pile	South	East - South - East
Measurement platform	Vessel	Autonomous System

3.2 Bubble curtain model

The computational domain has been chosen to 915 m*33 m as length and height considering an overall soil layer thickness of 10 m. The properties of the soil and the bubble curtain have been set according to table 2 and 3. The bubble size distribution is close to not yet published measurements conducted in a water basin in 4.25 m depth in the project BORA. The properties of the air have been chosen by standard literature (11) for a temperature of 15 degree Celsius. The gas thermal diffusity which is dependent on the static pressure has been linearly interpolated for every depth.

Table 2 – Soil properties

Layer	z, m	c_c, m/s	c_s, m/s	α_c, dB/λ	α_s, dB/λ	c_{eff}, m/s	ρ, kg/m^3
Water	-	1480	-	-	-	1480	1025
1	2	1734	187	0.89	1.87	1748+i*29	1877
2	8	1725	277	0.88	2.77	1755+i*30	1907

Table 3 – Bubble Curtain parameters

Parameter	Value
Air flow in $m^3min^{-1}m^{-1}$	0.39
Bubble size distribution	Gauss
Average bubble radius in mm	3.5
Standard deviation in mm	2.0

3.3 Results

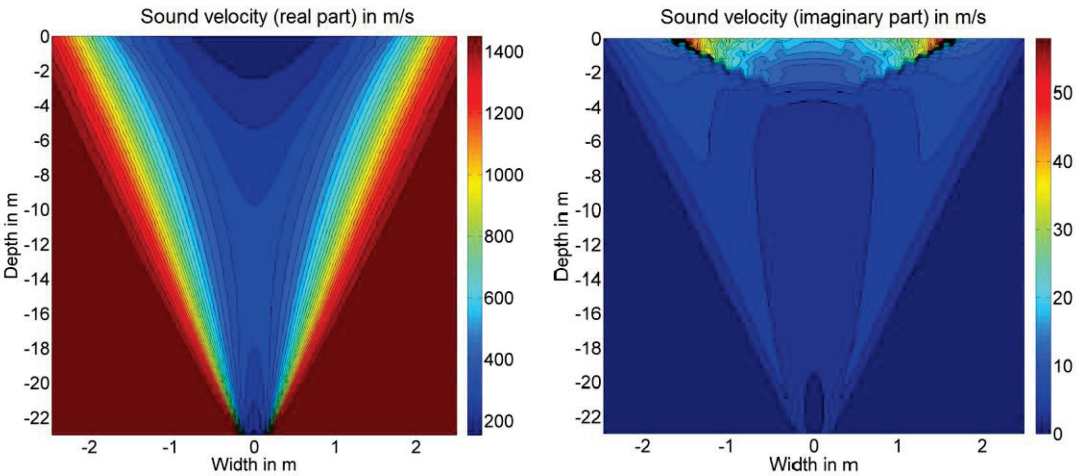

Figure 2 – Distribution of the sound velocity in the bubble curtain for a frequency of 348 Hz. (Left: real part, Right: imaginary part)

The bubble curtain interacts in different ways with the incoming wave. Mainly there are the reflection and the absorption of the wave. The former is related to the impedance contrast, which is characterized by the distribution of the real part of the sound velocity, between the ambient water and the water-bubble-mixture. The absorption properties of the bubble curtain are represented by the imaginary part. The distribution of the resulting sound velocity for the bubble curtain at FINO3 is plotted in Figure 2 (Left: real part, Right: imaginary part) exemplarily for a frequency of 348 Hz. The presence of bubbles in the water leads generally to a reduction of the sound velocity (real part). In particular, this can be observed around the central axis. The higher value on half depth has to be emphasized. The imaginary part in comparison diverges from zero only near the water surface. It should be noted that for higher frequencies approaching the eigenfrequencies of the bubbles the imaginary part increases.

Figure 3 shows the resulting absolute pressure distribution with and without (i.e. reference) bubble curtain up to 300 m distance to the pile for three frequencies. The pressure wave enters the domain on the left side under an angle of 18 degrees and is reflected by the bottom and the sea surface a few times. The insertion of the bubble curtain causes a shift of the wave direction for the lower and medium frequency range. The steeper angle effects a higher absorption by the bottom in comparison to the reference case.

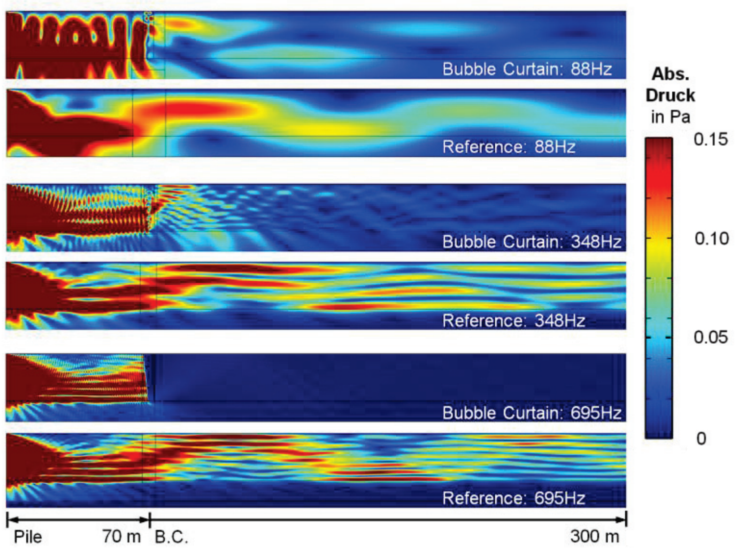

Figure 3 – Distribution of the absolute pressure for FINO3 with and without (i.e. reference) the bubble curtain for three frequencies

For higher frequencies the wave does not pass the bubble curtain directly due to the higher absorption rate. A small part of the incoming wave is guided by the top bottom layer. It should be noted that the increase of the absorption starts around the medium frequency range and causes for higher frequencies a closing of the bubble curtain from the top to the bottom. This can be explained by the higher eigenfrequencies of the bubbles in greater depth due to the increase of the static pressure.
The resulting transmission loss at the measurement positions is plotted and compared with the measurements in Fig. 4 (MP2: blue curves, MP3: red curves). The result for MP2 diverges from the measurement by around 5 dB. High accuracy between the measurement and model can be observed for MP3.

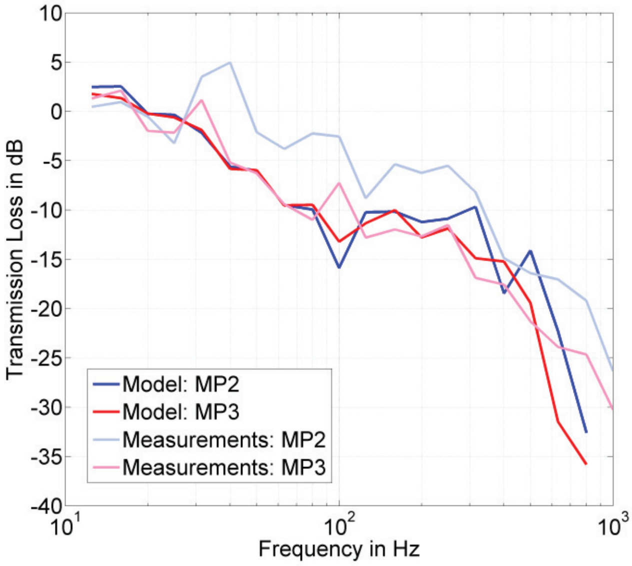

Figure 4 – Transmission Loss of the model and the measurements for the Positions 2 and 3 (Measurements: (10))

4. DISCUSSION

The discrepancy between the model results and the measurements at MP2 can be traced back to either a measurement error or, more likely, an inaccurate representation of the local offshore conditions. The main model assumptions are the axisymmetry of the problem, horizontal layered homogenous soil properties and the vertical undisturbed rising of the bubbles. The latter two are sensitive concerning the complexity of the bottom structure and the tidal flow in the North Sea. Due to missing information on soil properties and tidal flow direction a further discussion is not possible.

5. CONCLUSIONS

The developed model follows an integral approach to represent the local acoustical behavior of the bubble curtain by coupling a fluid model with a bubble acoustic model. The direct insertion in a sound propagation model permits to study the acoustical behavior of the bubble curtain in frequency domain under offshore conditions. The results have been compared with measurements during the construction of the FINO3 research platform. The noise mitigation of the bubble curtain in the lower and medium frequency range can be traced back to the shift of the wave pattern causing higher wave absorption by the bottom. In particular this frequency range is characterized by high sound pressure levels during the construction.

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