Measurement and Reduction of Offshore Wind Turbine Construction Noise

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Summary

Both operation and construction of offshore wind turbines induce underwater noise. While it is not yet clear if operating noise affects the behavior of marine animals, construction noise is considered crucial. Common foundation techniques require to drive steel tubes up to 30 m into the seabed. In general, hydraulic pile hammers are used for this purpose. During the erection of a 3.5 m monopile, peak sound pressure levels of more than 180 dB re 1 µPa have been measured at 1 km distance from the pile driver.
These levels are potentially harmful to marine mammals like harbor porpoises and induce flee reactions in a large area. Due to larger piles requiring higher blow energies, even higher levels are expected in future projects. Hence, noise reduction is mandatory.
Within a joint research project, a concept of practicable noise reducing methods is derived from measured results and numerical simulations on construction noise of offshore wind turbines. Theoretical background and technical realizations are discussed in this paper. Furthermore, results of numerical simulations and of scaled and near full scale experiments are shown.
There are two main approaches:
1. Adjusting the parameters of the pile stroke,
2. Use of sound barriers.
One of the key parameters of method 1 is stroke duration. Prolonging the impulse not only reduces the sound level, but also shifts the maximum of the acoustic spectrum to lower frequencies, which are less harmful to marine mammals. Vibration pile driving, where applicable, also considerably reduces the sound level with respect to impulse pile driving, in particular the peak level. Underwater noise measurements of vibrohammer are compared to impulse hammer.
Method 2 includes various techniques like the well-known bubble curtain, but also noise barriers based on sound impedance mismatch between the barrier material and water.
Both method 1 and 2 are mutually independent; when used in combination, their efficiency simply adds up in terms of dB numbers and a very high degree of noise reduction is achieved.
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Introduction

The Institute for Structural Analysis (ISD) of the Leibniz University of Hannover, the German Wind Energy Institute (DEWI) in Wilhelmshaven, and the Institute for Technical and Applied Physics (itap) in Oldenburg are partners in a prolonged project on: 'Standard Procedures for the Determination and Assessment of Noise Impact on Sea Life by Offshore Wind Farms' which is funded by the German Federal Ministry of Environment (BMU).
The aim of this project is to determine the impact area of offshore wind farms, to allow the formulation of recommendations for acoustic emission thresholds of offshore wind farms in cooperation with biologists, to study the generation, radiation and attenuation of underwater noise and to derive a concept of noise reduction methods during pile driving of offshore foundations.

The operation and in particular the construction of offshore wind energy converters (Fig.1) induce considerable underwater noise emissions. Extensive measurements and numerical simulations of monopiles and jacket foundations under construction result in maximum underwater sound pressure levels of more than 200 dB re 1 μPa nearby during pile driving and in considerable noise levels several ten kilometres away. This noise has possible effects on marine life, but is not known enough till now to formulate exact acoustic emission limits and assessment procedures.

Figure 1: Hydraulic hammer on a pile of FINO1.

It is assumed that small whales and seals can be affected by noises from machines and vessels, piling and installation of the wind turbines.
The immission limit value of 160 dB at 750 m derived from audiograms of harbour porpoises results from cooperations with biologists

Measured Underwater Noise Emissions

Piling, in particular using hydraulic hammers creates high frequency noise with considerable underwater sound levels.

Impulse noise like pile driving noise is described by two sound levels. The first level is the *peak level*,

$$L_{peak} = 20 \log_{10} (| p_{peak} | / p_0),$$

where p_{peak} is the maximum positive or negative sound pressure observed and p_0 is 1 μPa .
The second quantity for describing pile driving noise is the *single event sound pressure level* L_E (sometimes also abbreviated SEL), which is basically normalized to 1 second:

$$L_E = 10 \log \left(\frac{1}{T_0} \int_{t1}^{t2} \frac{p(t)^2}{p_0^2} dt \right)$$

The time interval T_0 is set to 1 s.
Fig. 2 shows the underwater sound pressure of a single stroke of a hydraulic hammer, measured at a distance of 1.6 km.

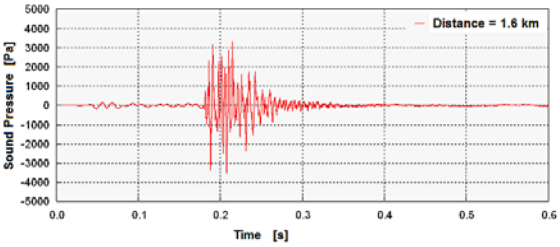

Fig. 2: Measured sound pressure of a single stroke.

The contact time of a hydraulic hammer is 4 ms and the signal length of the resulting sound radiated from the vibrating pile takes about 200 ms.

This single sound event in Fig.2 exhibits a maximum peak sound pressure of about:

$$p_{peak} = 3500 \text{ Pa},$$

leading to the logarithmic *peak sound pressure level* of:

⇨ $L_{peak} = 191$ dB re 1μPa,

and to the *single event sound pressure level* (as an equivalent energy level) of:

⇨ $L_E = 167$ dB re 1μPa.

The underwater noise emissions of offshore pile driving during construction of different objects in Table 1 are measured at a distance of about 750 m.

Measured Noise Emissions:

Object	Pile diam. [m]	Energy [kNm]	Lpeak [dB]	LE [dB]
Port construction, coast	1.5	280	184	158
Monopile Sky2000, Baltic S.	3.0	280	185	164
FINO1 (Jacket), North Sea	1.5	280	189	164
Monopile Amrumbank, N.Sea	3.5	800	200	175
5 MW – OWEC (expected)	6.0	1600	>205	>178

Table 1: Measured pile driving underwater noise emissions at a distance of 750 m.

Peak sound pressure levels of

$$L_{peak} > 180 \text{ dB re } 1\mu\text{Pa}$$

and single event sound levels of

$$L_E > 160 \text{ dB re } 1\mu\text{Pa}$$

are potentially harmful to marine mammals and other marine animals.

In Germany, several large offshore wind farms with several hundred turbines of about 5 MW are planned in the North Sea and the Baltic Sea. This increase of the installed power per unit is accompanied by an increase of the expected construction noise from pile driving.
Because of the high hydro acoustic levels, a concept of practicable noise reducing methods is derived from measured results and numerical simulations on construction noise of offshore wind turbines.

General Aspects of Noise Reducing Methods

Only a very small amount of the impact energy of a hydraulic hammer is radiated directly into water as hydro sound after Fig. 3.

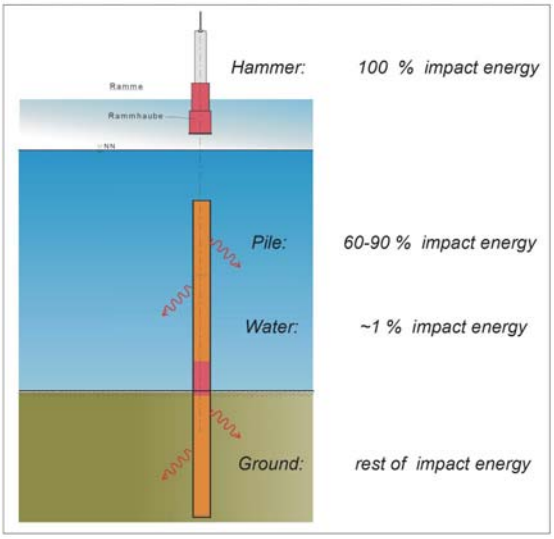

Fig. 3: Balance of the whole ram energy.

But this small amount of energy is responsible to the very high hydro sound levels. Most of the energy is driven into the ground and is vanishing by dissipation. Energy transfer from the ground into the water is possible, mainly from dense soil material. In general this noise is less important than the noise directly radiated from the pile.

There are two main approaches to noise reducing methods of construction noise:

1. Primary noise reducing methods with changing the excitation (active method) like:
   - Adjusting the parameters of the pile stroke and prolonging the impulse contact time;
   - Using vibrators for small piles instead of impact hammers.
2. Secondary noise reducing methods with changing the transmission path (passive method) like:
   - Using a curtain of air bubbles around the pile;
   - Putting a foam coated tube as noise barrier over the pile.

Prolonging the Impulse Contact Time

Numerical FE-simulations in Fig. 4 show, that the radiated hydrodynamic sound pressure depends on the velocity of lateral pile vibrations.

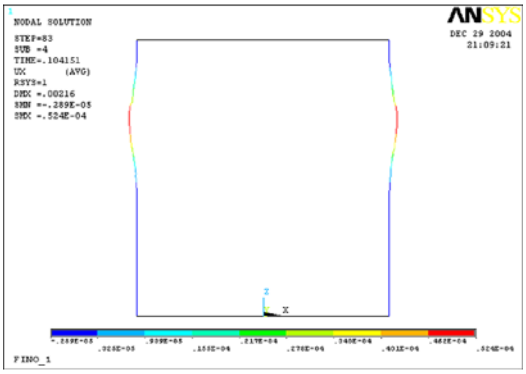

Fig. 4: Velocity amplitudes of pile vibrations induce hydrodynamic sound pressure.

Using the same ram energy but prolonging the contact time of the hydraulic hammer after Fig. 5 results in smaller impact forces and thus generates smaller velocity amplitudes of pile vibrations.

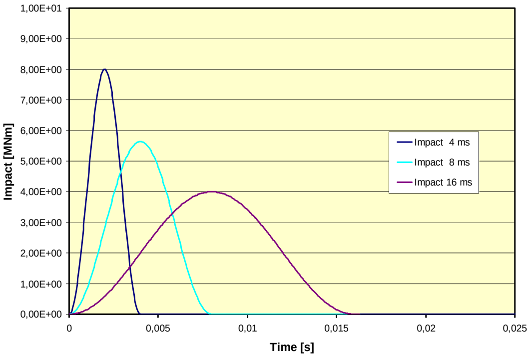

Fig. 5: Impact forces of different impulse contact times with the same ram energy.

The extension of the pulse duration from 4 ms to 8 ms, for example by inserting a "soft" layer between pulse hammer and pile, leads to about 9 dB noise reduction of the peak sound pressure level L_{peak}:

- 3 dB, as smaller impact forces generate smaller velocity amplitudes, and additional
- 6 dB, as longer contact times result in lower frequencies and smaller velocity amplitudes.

Within certain bounds the penetration of a driven pile only depends on the amount of impact energy of one stroke and not on the impact force. The results of pile driving with different impact forces but the same energy after Fig. 5 are nearly the same.

The reduction of energy based sound levels like the single event sound level and the third octave analysis is smaller than the reduction of the peak sound pressure level, as the impact energy remains the same.

Using Vibrators for Small Piles

Another primary noise reducing method is using unbalanced vibrators for pile driving of small piles into an appropriate ground instead of using a hydraulic hammer. An impact hammer induces underwater noise in a large frequency range of up to several thousands Hz after Fig. 6.

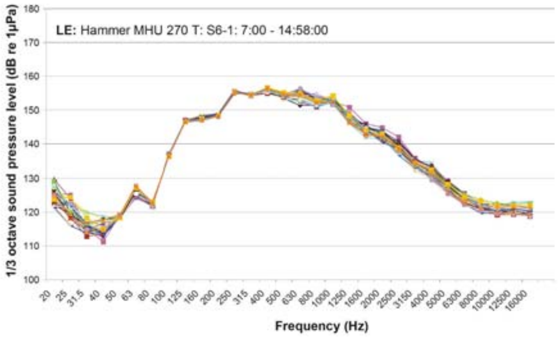

Fig. 6: Noise spectrum of an impact hammer.

Unbalanced vibrators operate with continuous vibrations of frequencies between f ≅ 20 ÷ 40 Hz. Most of the noise is radiated within this frequency range after Fig. 7, to which mammals do not react very sensitively.

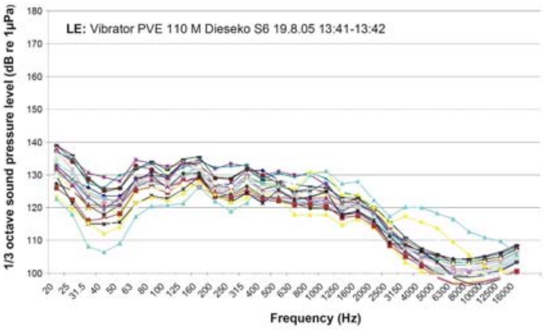

Fig. 7: Noise spectrum of a vibrator.

The noise reduction during pile driving when using vibrators is about 15 – 20 dB. But pile driving using vibrators is limited to certain soils and small piles.

Curtain of Air Bubbles

In secondary, passive noise reducing methods the transmission path of the acoustic noise immission into the water is modified.

A curtain of small air bubbles in the water around the pile reduces the underwater sound propagation.
Water, filled with air bubbles, is compressible and acts like a discontinuous absorbing medium. Scattering, multiple reflections of travelling acoustic waves and mainly the dissipation of vibrating air bubbles reduce the noise transmission.
The single vibrating air bubble is a point monopile with the dissipation factor strongly depending on frequency and bubble diameter. The characteristic curve of attenuation of an air bubble curtain in Fig. 8 also depends on the air bubble concentration in the water.

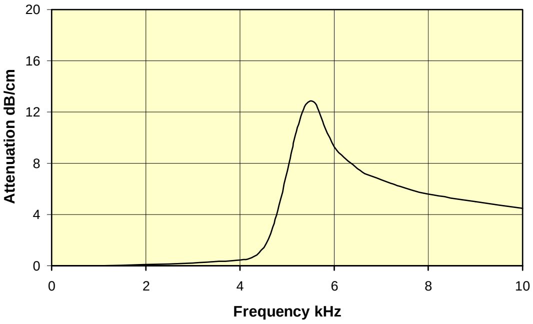

Fig. 8: Characteristic curve of attenuation of an air bubble curtain.

In the example of Fig. 8 the air concentration is about $5*10^{-5}$ and the diameters of the air bubbles are between 0.6 and 0.7 mm. The attenuation effect of the bubble curtain is to be seen above the resonance frequency of about 5 kHz and shows its maximum near the resonance frequency of the air bubbles.
In practical applications noise reductions between 5 and 20 dB are realized. But according to the strong currents in the Baltic Sea and especially in the North Sea with a flow velocity of 2m/s, it is an unsolved problem to keep the air bubble curtain concentrated around the driven pile in water depths up to about 30 – 40 m.

Coated Tube as Sound Barrier

A noise barrier, based on solid material sound impedance mismatch between the barrier material and water is another secondary, passive noise reducing method with modifying the transmission path.
In the Baltic Sea, a foam coated tube of 2.2 m diameter after Fig. 9 was put over a pile. The tube of steel and the coated foam material layer of 5 mm are discontinuities on the transmission path of the traveling sound waves. The attenuation of sound waves, passing through this barrier of different materials strongly depends on the materials different products of sound velocity and density. Each transmission of waves from one material to another and into the water is accompanied by reflections and energy lost with the effect of reducing the acoustic noise immission into the water.

A steel tube alone or a rubber layer only show small noise reduction after Fig. 10. With a foam coated steel tube noise reductions of 5 to 25 dB (depending on frequency) are measured after Fig. 10.

Fig. 9: Coated tube over a pile in the Baltic Sea.

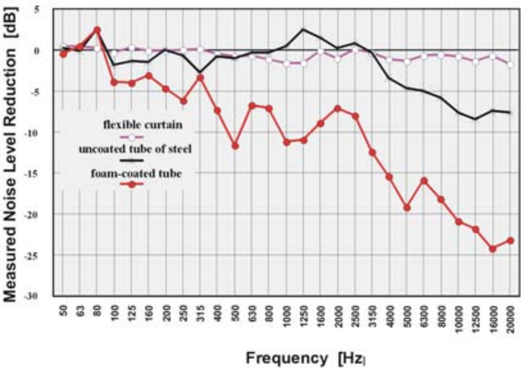

Fig. 10: Frequency dependent noise reduction.

Much larger values were recently achieved on a scaled sound barrier model made of a foam layer between polyester tubes.

Conclusions

The high hydro noise levels during pile driving of offshore wind converters are potentially harmful to marine mammals like harbor porpoises.
Practical noise reducing methods are derived from measured results and numerical simulations. The suggested active and passive methods achieve noise reductions up to between 10 and 20 dB alone, and more, when used in combination.

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