EFFECTIVE MITIGATION METHOD FOR OFFSHORE PILING NOISE

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1 INTRODUCTION

Hydraulic impact hammers induce considerable underwater sound emissions. During the founding of offshore wind turbines by means of impact pile driving, peak sound pressure levels have been measured high above 200 dB re 1 µPa at a distance of 750m from the pile driver. This construction noise of offshore wind turbines is potentially harmful to marine life, in particular to marine mammals. These noise immissions induce flee reactions in a large area, as water is a very efficient conductor of sound. Even higher underwater noise levels are expected in future offshore projects and this is also accompanied by an increasing number of erected offshore wind turbines. Hence, effective noise reducing methods like the new mitigation method of Hydro Sound Dampers (HSD) are in great demand to achieve the German Federal Maritime and Hydrographic Agency (BSH) standard level of 160 dB (SEL) re $1\mu Pa^2s$ at a distance of 750m from offshore piling.

2 IMPACT PILING NOISE

2.1 Problem of offshore piling noise

Underwater noise from offshore impact piling result in considerable sound emissions that are distinguishable above ambient noise over distances of up to 50 km from the source as given in Elmer et al. (2007)[1]. This construction noise of offshore wind turbines is potentially harmful to marine life, in particular to marine mammals as reported by Southall et al. (2007)[2] and Lucke et al. (2009)[3]. Different zones of underwater noise immissions can be defined in the surrounding of a source of underwater noise. The ranges of these noise zones strongly depend on the kind of hydraulic impact hammers and possible noise mitigation methods.

On the other side, different injury ranges for different mammals are described by Thomsen et al. (2006)[4], Southall et al. (2007)[2] and Lucke et al. (2009)[3]. Within the zone of audibility of several kilometers up to several tens of kilometers with moderate exposure levels, marine animals like harbour porpoises, harbour seals, grey seals and also fish will show some kind of reaction or change in their behaviour. At higher exposure levels, within the closer zone of several hundreds of meters from the source up to several kilometers in the case of harbor porpoises, underwater noise can induce temporary (TTS) or permanent (PTS) threshold shift. Important acoustic information might be masked caused by reductions in hearing sensitivity of an animal. Close to a very loud source of noise like impact pile driving, extreme intensity levels of underwater noise can cause physical trauma or death.
Even the lowest level of damage, which is a temporary threshold shift (TTS), is dangerous and must be avoided.
Due to larger piles requiring higher driving energies, even higher underwater noise levels are expected in future offshore projects and this is also accompanied by an increasing number of erected offshore wind turbines. Effective noise reducing methods are in great demand, getting sound levels below recommended acoustic emission thresholds that are no longer harmful and disturbing to marine mammals and other protected animals.

2.2 Radiation and Propagation of piling noise

Numerical simulations and measurements of the impacts of a pile hammer show that the resulting traveling waves within the offshore piles are reflected up to several times at stepped cross sections of the piles and at both ends of the piles after Figure 1, until all the kinetic energy is damped out and is radiated into the sea ground. Obviously, these traveling waves induce sound waves in the surrounding water, propagating with the speed of sound of water of about 1500m/s into all directions of the shallow water after Figure 1, reflected at the free water surface and at the sea ground.

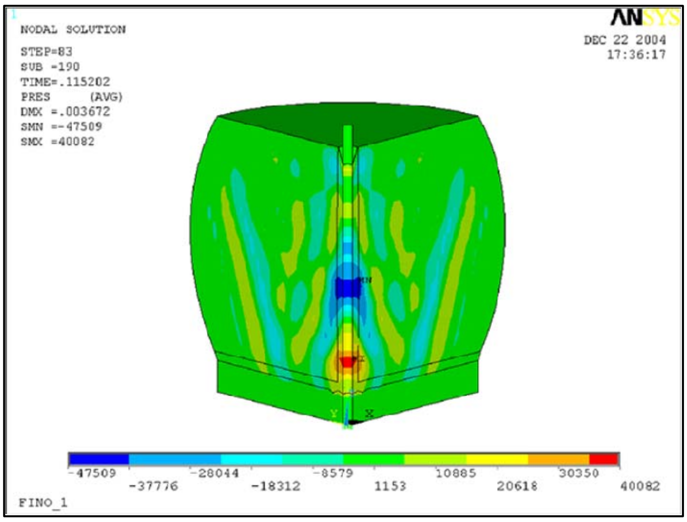

Figure 1: Traveling impact wave of a pile inducing underwater sound waves and reflections of the sound waves at the free surface of the water and at the sea ground after Elmer (2004)[1].

After Figure 2, this direct radiation of sound energy is due to dilatational displacements of the traveling waves in the pile. But it is only about 1% of the whole ram energy that is radiated directly from the wet surface into the surrounding water inducing very high sound levels. Most of the impact energy of the hydraulic hammers is driven into the sea ground.

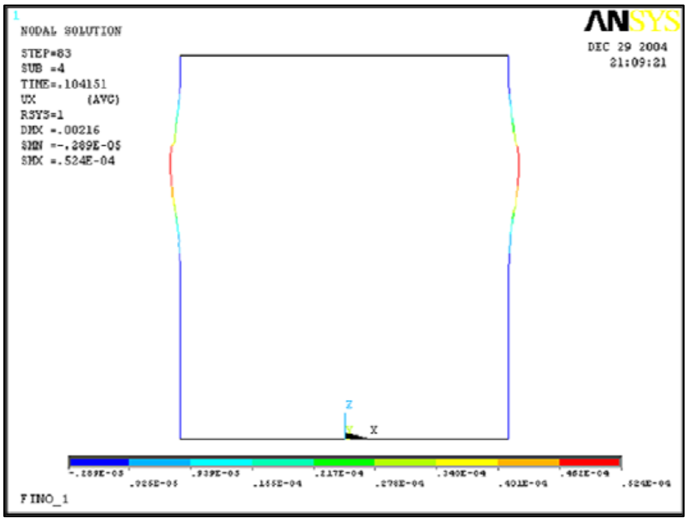

Figure 2: Direct radiation of underwater noise due to dilatational displacements of the traveling impact wave in a pile, Elmer (2004)[1].

Depending on the properties of the ground material one part of the impact energy is radiated indirectly from the sea ground into the water, resulting in additional underwater sound, even far away.

3 NOISE MITIGATION OF AIR BUBBLE CURTAINS

Spectral information of pile strokes are given by third-octave spectra of the sound exposure levels (SEL) of three different hydraulic hammers in Figure 3. The highest spectral levels of the measured underwater ram noise of the hammers are shown in the low frequency range from 100 to 300 Hz, responsible to the high broadband level of piling noise.

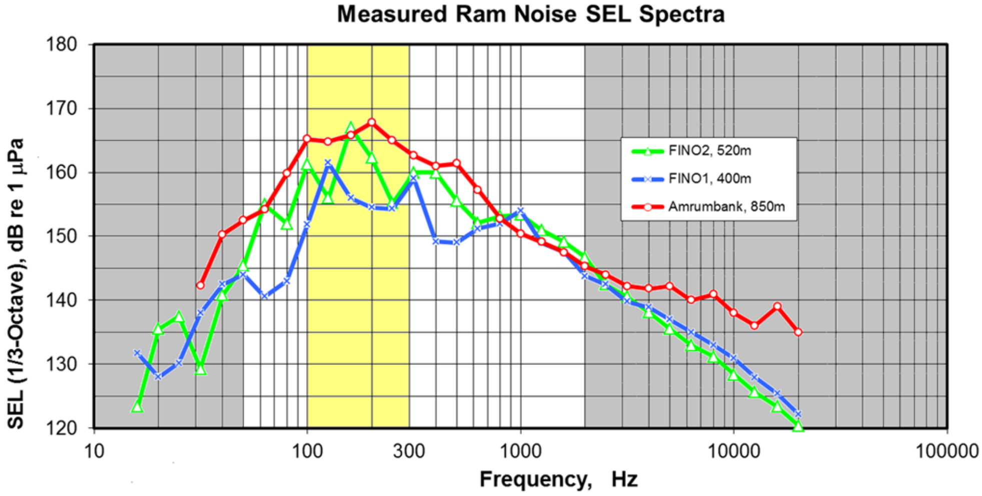

Figure 3: Third octave spectra of measured underwater noise of different offshore projects, Betke (2008)[5]

In Germany, first offshore applications of air bubble curtains achieved only small noise reductions during pile driving operations of the offshore platforms FINO3 as described by Betke (2008). The problems are sound leakage through the bubble curtain resulting from bubble drift with tidal currents. Therefore, the sizes of diameters of unconstrained bubble curtains around offshore piling sites are between 140m and 250m.
After Figure 4, the attenuation of air bubble curtains in the high frequency range above 1 kHz is very high. But the broadband sound level of the piling noise mainly depends on the lower frequency noise, far below 1 kHz, where the attenuation from bubble curtains is only poor.

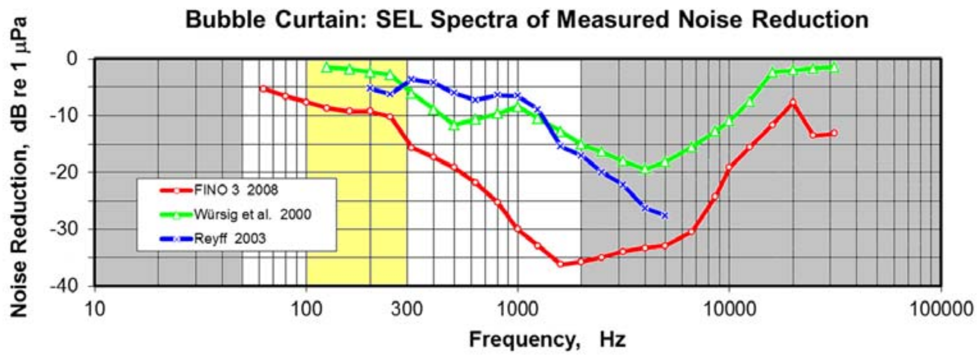

Figure 4: Noise reductions of bubble curtains, Betke (2008)[5]

The reasons for this are, that large air bubbles (several cm) with low resonant frequencies are uncontrolled, showing chaotic movements and dividing themselves when they are slowly arising to the surface of the water. The attenuation of air bubbles is only poor in the most important frequency range between 100 - 300Hz after Fig. 4. Modern hydraulic impact hammers even tend to most important frequency ranges between about 50 - 200Hz.

Offshore applications of air bubble curtains are very expensive at great water depth and currents. The main problems are the supply with compressed air, the control of the bubble size or the control of bubble distribution, and the influence of the tide currents of the sea, together with slow ascent rates of the bubbles.
The German Federal Maritime and Hydrographic Agency (BSH) has set the standard sound exposure level of 160 dB (SEL) and the peak level of 190 dB (SPL) at 750m distance from offshore pile driving sites as part of the building permission of offshore wind farms.
Effective noise reducing methods are necessary to achieve these standard levels.

4 THEORETICAL NOISE ATTENUATION OF BUBBLES

The theory of bubble acoustics is used to develop a new effective noise mitigation method as air is the best medium to reduce underwater sound.
The resonance frequency f_{Res} of an air bubble in water at depth z meters and of the bubble radius *a* is depending on the ambient water density $\rho_A = 1.03 \times 10^3$ kg/m^3, the ambient static pressure at the depth *z* of $p_A = 10^5 (1+0.1z)$ N/m^2 and the ratio of specific heats $\gamma = c_p/c_v = 1.4$ for the enclosed gas under constant pressure c_p and volume c_v is approximated by the following Minnaert equation:

$$f_{\mathrm{Res}} = \frac{1}{2\pi a}\left(\frac{3\gamma\, p_A}{\rho_A}\right)^{1/2} \quad (1)$$

or:

$$f_{\mathrm{Res}} \cong \frac{3.25}{a}\left(1+0.1z\right)^{1/2} \quad (2)$$

The whole extinguished power Π_e of a bubble, as the sum of scattered sound power Π_s and absorbed sound power Π_a, is referenced to the incident plane wave intensity I_{inc} of the bubble to get the extinction cross section σ_e after Medwin,(2005)[6]:

$$\sigma_e = \frac{\Pi_e}{I_{inc}}, \quad (3)$$

With the damping constant δ as the sum of all damping constants due to re-radiation or scattering $\delta_r = ka$ plus thermal conductivity δ_t and shear viscosity damping δ_v the extinction cross section σ_e can be calculated after Medwin,(2005)[6] from:

$$\sigma_e = \frac{\Pi_e}{p_{inc}^2/\rho_A c} = . \frac{4\pi a^2\left(\delta/\delta_r\right)}{\left[\left(f_{\mathrm{Res}}/f_{inc}\right)^2 - 1\right]^2 + \delta^2}, \quad (4)$$

where the extinguished power is obtained from the rate at which work is done on the bubble by the incident pressure $p_{inc.}$. At resonance the extinction cross section σ_e of a bubble is much larger than its physical geometric cross section.
The extinguished power of an incident plane wave of intensity I_{inc} by each bubble is $I_{inc}\,\sigma_e$. Assuming *N* resonant bubbles of the same size, the change of intensity over a distance *dx* is:

$$dI = -I_{inc}\sigma_e N\, dx. \quad (5)$$

The integration of the change of intensity over *x* results in:

$$I_x = I_{inc}\, e^{(-\sigma_e N x)} \quad (6)$$

and for the sound pressure in:

$$p_x^2 = p_{inc}^2 \, e^{(-\sigma_e N x)} \qquad (7)$$

After Medwin (2005)[6] the change in sound pressure level ΔSPL of a sound wave is:

$$\Delta SPL = 20\log_{10}\frac{P(x)}{P_p} = -10\sigma_e N x \log_{10} e \qquad (8)$$

after traversing the distance *x* in water due to bubbles of the same size where $\sigma_e N$ is the extinction cross section of the bubbles per unit volume of the water.
The attenuation per unit distance due to N bubbles per unit volume is:

$$\alpha_b = -\frac{\Delta SPL}{x} = 4.34\sigma_e N \qquad \text{dB/distance.} \qquad (9)$$

Figure 5 shows examples of attenuations in dB/m of only single bubbles per unit volume for different bubble sizes. Therefore, also the resonance frequencies and the volume rates of air are different.

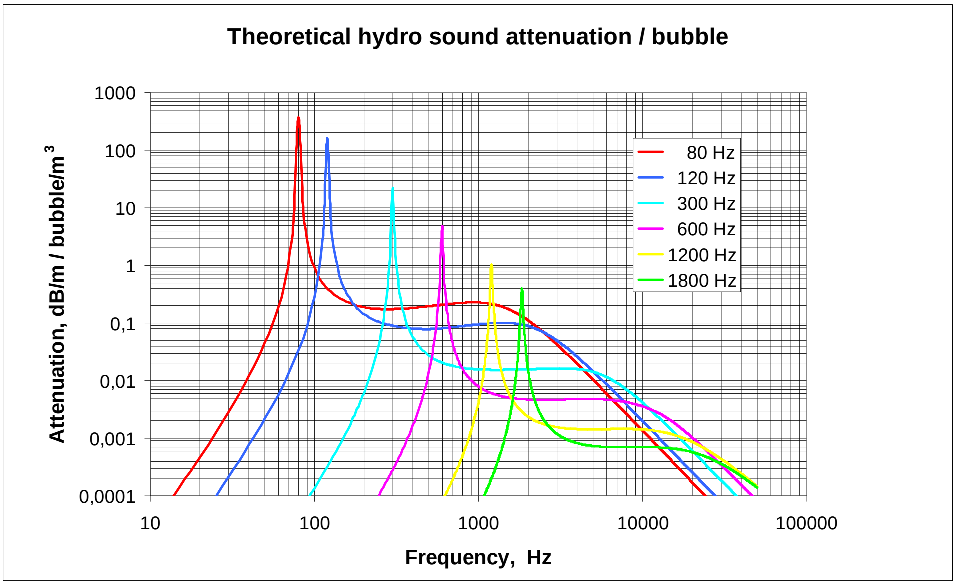

Figure 5: Theoretical spectrum of sound attenuation in dB/m due to single bubbles per unit volume of different resonance frequencies for each meter of traverse traveling sound waves, Elmer (2010)[7].

The spectrum of sound attenuation of Figure 5 only shows theoretical resonance effects of the lower frequency bubbles. They are not real as larger bubbles of several centimetres, with resonance frequencies below 1 kHz, are not stable in praxis, showing chaotic movements and dividing themselves when they are slowly arising to the surface of the water. They only show poor resonant effects.
Against this, only constant shapes of air bubbles and nearly steady state resonance excitations are able to achieve high sound attenuations of resonant air bubbles. As a consequence there is no benefit from high theoretical underwater sound attenuation potential of large air bubbles with low resonance frequencies, as shown in Figure 5, when using conventional air bubble curtains.

An effective noise mitigation method must be able to reduce the noise levels even in the most important lower frequency range of underwater piling noise after Figure 3 with the noise level decisive frequency range between 100 - 300Hz.

5 HYDRO SOUND DAMPERS (HSD)

To overcome these problems, a new underwater noise reducing method is developed, using gas filled envelope bodies and PE-foam elements as encapsulated bubbles, named hydro sound dampers (HSD), instead of natural air bubbles, as first developed and published by Elmer (2010)[7].

The size of the bodies, the effective frequency range, the damping rate, the number and distribution of the hydro sound dampers (HSD) and the influence from hydrostatic pressure can be fully controlled, if the envelope bodies are fixed to a pile surrounding fishing net or to stiff frames.
Figure 6 shows HSD offshore applications as staggered HSD-grids or large fishing nets with HSD-elements round a pile. Systems of hydro sound dampers can also be fixed to the hammer, a piling frame or a gripper after Figure 7. Covering the whole sea in the near of a pile to reduce the indirect noise, transmitted from the ground into the water is another HSD offshore application. The efficacy of HSD in reducing underwater noise depends on the frequency and the volume rate of the hydro sound dampers. Rates of about 1-2% of the HSD are sufficient to obtain good results. At these volume rates vertical forces from buoyancy and horizontal forces from tide currents are still small.

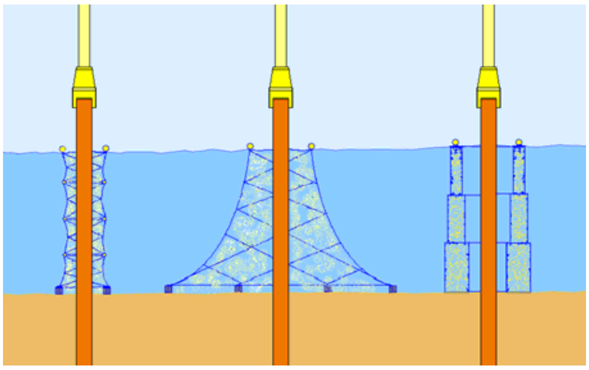

Figure 6: Staggered HSD-net, large fishing net and telescopic frames, Elmer (2010)[7].

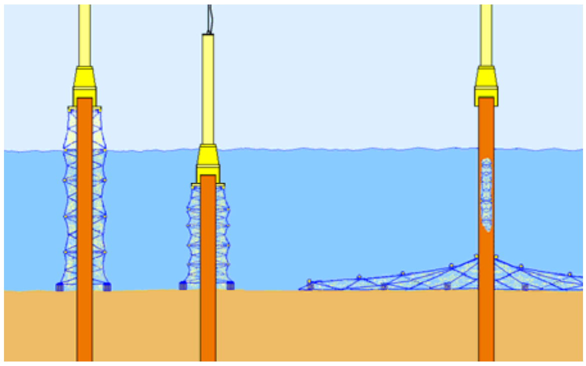

Figure 7: HSD-net fixed to a ram or piling frame or covering the ground, Elmer (2010)[7].

The important resonance effect with high scattering, multiple reflections and effective absorption of sound waves at water surface is to be seen in Figure 8. The very strong interaction of a vibrating HSD-element also takes place under water as shown in Figure 9, but it is not visible there.
In contrast to conventional air bubbles, hydro sound dampers of both kinds, gas filled bladders and PE-foam elements are using three different physical effects for underwater noise attenuation:

- Reflections of sound waves at impedance steps from water, filled with hydro sound dampers,
- Resonance effects with high scattering, multiple reflections and absorption of sound waves,
- Dissipation of acoustic waves according to material damping effects of HSD elements.

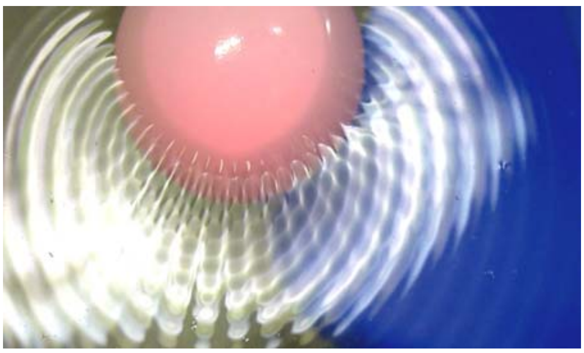

Figure 8. Scattering, radiation and strong interactions of a vibrating HSD, Elmer et.al. (2011)[8].

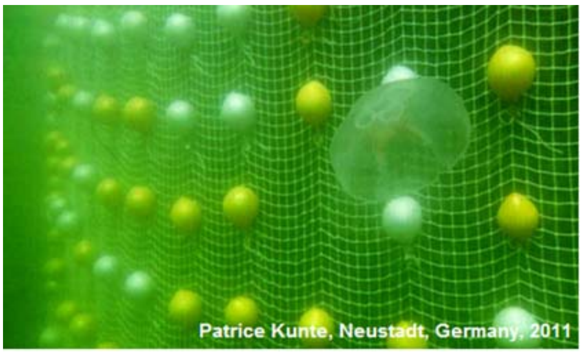

Figure 9. HSD-net and elements under water.

6 OFFSHORE NOISE REDUCTIONS OF HSD-SYSTEMS

Offshore test results in the Baltic Sea confirm the high underwater sound attenuation of both, gas filled balloons and PE-foam elements. The first tested HSD-System is a self-swimming construction of 10t weight after Bruns (2012)[9]. All elements are tuned to the resonance frequency of 120 Hz. The net layout with blue colored HSD-elements is to be seen in Figure 10. The radiated noise was measured at 4 m above the ground at a distance of 6 m from the pile to get most of the directly radiated sound and to avoid influences of reflections from the sea ground. Figure 11 shows the SEL spectrum of noise mitigation. There is a very broad noise reduction up to 23 dB (SEL) within the most important range of 100 - 600 Hz after Bruns et.al. (2012)[9].
That means, 99.5% of the sound energy is damped out although the HSD-net is only covered by less than 10% of its surface. Higher frequencies and smaller elements are not tested.

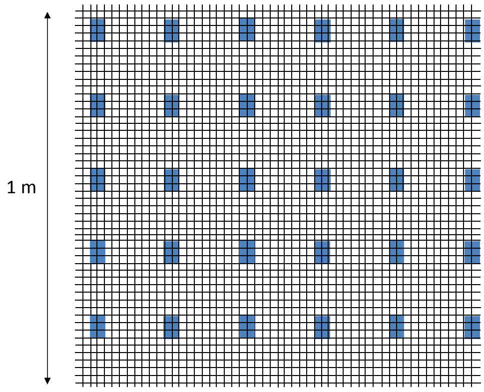

Figure10. HSD net-layout at ESRa-Test[9] in the Baltic Sea in 2011.

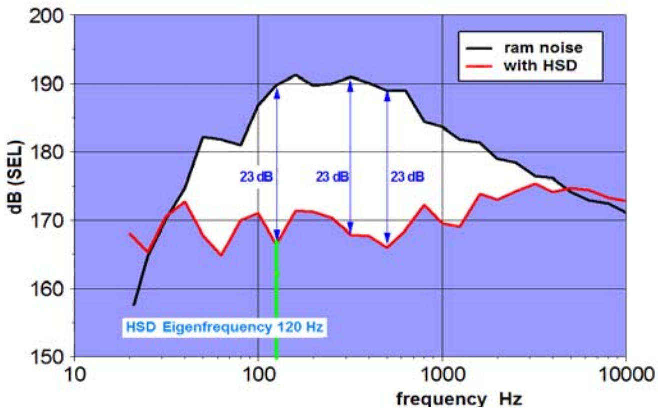

Figure 11. Third octave SEL spectra of underwater piling noise with and without HSD noise mitigation.

Another offshore test was done at the London Array (LA) wind farm in August 2012 in the North Sea nearby the coast of the United Kingdom. The designed HSD is a self-expanding system with a total weight of only 17t and a diameter of 9 m after Figures 12-14. There are three parts: the buoyancy ring at the water surface, the HSD net and the ballast box. The compressed HSD has a height of 1,8m and is applicable in variable water depth of up to 28m as described by Bruns et. al. (2012)[9].

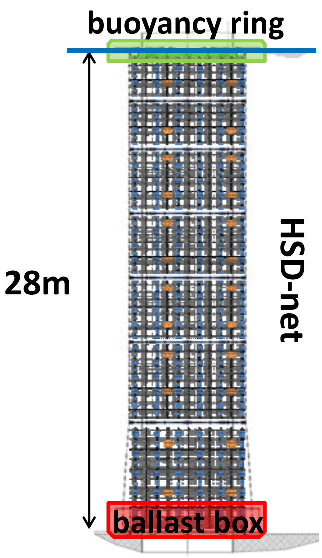

Figure12. HSD-net, LA test[9].

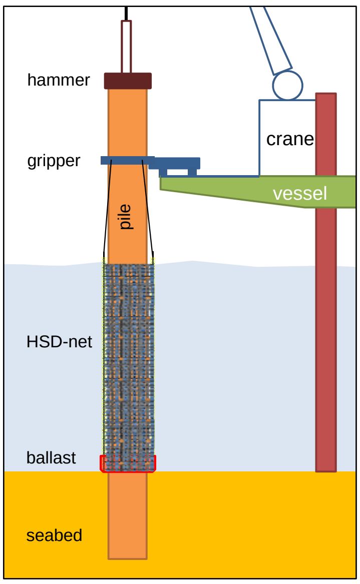

Figure 13. Net below the gripper[9].

Figure 14. London Array test[9].

The net layout of LA in Figure 15 shows the same compilation of HSD elements as used before. In addition to that, smaller and larger elements are applied to get a better noise reduction in the frequency range below 100 Hz and higher than 1000 Hz. The underwater sound mitigation was measured at 1 m above the seabed at a distance of 15 m. Figure 16 shows the 1/3 octave SEL spectrum of the original piling noise and reduced noise with HSD in use.

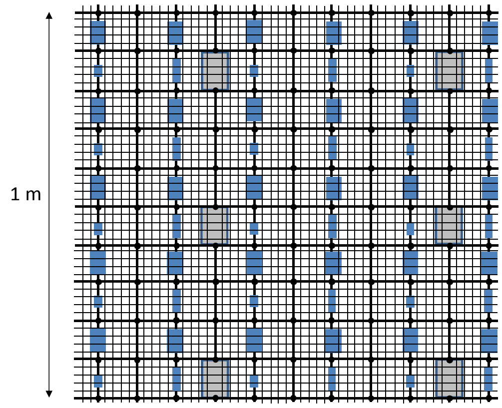

Figure15. HSD net-layout at London Array test in the North Sea in 2012[9].

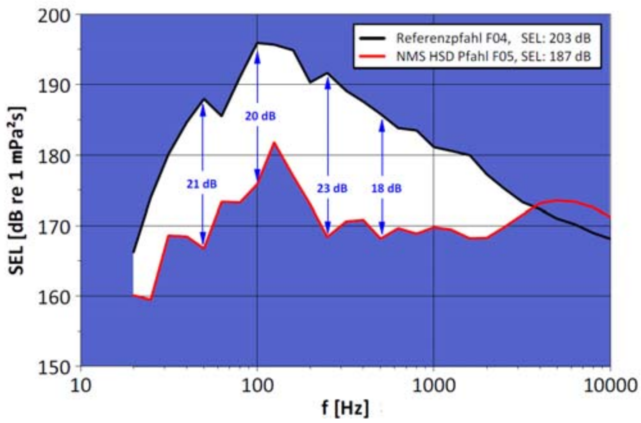

Figure 16. Third octave SEL spectra of underwater piling noise with and without HSD noise mitigation[9].

The impact of the additional applied HSD-elements causes increased reductions up to 21dB between 20-100 Hz and above 1kHz. Again there is a very broad noise reduction of up to 23 dB (SEL). HSD-systems are already patented in Germany since 2010, international PCT patents are pending.

7 ACKNOWLEDGEMENTS

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