Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering
OMAE2012
July 1-6, 2012, Rio de Janeiro, Brasil

OMAE2012-83707

DEVELOPMENT OF A NEW UNDERWATER PILING NOISE MITIGATION SYSTEM - USING HYDRO SOUND DAMPERS (HSD)

Christian Kuhn, Benedikt Bruns,
Jan Fischer, Jörg Gattermann
Institute for Soil Mechanics and Foundation Engineering
Technische Universität Braunschweig
Beethovenstraße 51b
D-38106 Braunschweig, Germany

Karl-Heinz Elmer
OffNoise-Solutions GmbH
Leinestrasse 36
D-31535 Neustadt am Rübenberge, Germany

ABSTRACT

The aim of the recently published climate control by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) is a reduction of the German greenhouse gas emissions down to 20 % in 2050, compared to the generated greenhouse gas in 1990. To reach the given target a huge growth in renewable energy is necessary. One of the most potential possibilities to produce renewable energy in Germany will be the installation of offshore wind turbines.

During the installation of offshore wind foundations such as monopiles, tripods, tripiles and jackets, mostly large tubular steel piles are impact driven to final penetration depth. In the process of impact driving, considerable underwater sound emissions will appear. In recent times, peak sound pressure levels above 190 dB re 1 µPa have been measured at a distance of 750 m away from the installation ground. These peak sound pressure levels, produced during the installation of any kind of driven offshore foundation, is potentially harmful to marine life, in particular to marine mammals such as harbor porpoises, harbor seals or grey seals.

To protect the marine life the German Federal Maritime and Hydrographic Agency (BSH) set the maximum allowed underwater sound pressure level to 160 dB (SEL) at a distance of 750 m away from pile driving.

To reach the given target by the BSH a new underwater piling noise mitigation system using so called hydro sound dampers (HSD) is presently developed at the Institute for Soil Mechanics and Foundation Engineering at the Technische Universität in Braunschweig (IGB-TUBS). After small scale tests in the so called 'large wave channel' in Hannover a full scale test was performed in the Baltic-Sea some weeks ago.

The results of the measurements are very promising, as a reduction of 12 up to 20 dB could be generated. Besides existing noise mitigation systems one of the main advantage of the hydro sound dampers is, that the mitigation can be pre-adjusted to a predefined frequency range, as marine mammals are sensitive only for a certain sound frequency range.

In this paper, the results of the small and large scale tests and some new research findings concerning the shape and the material of the hydro sound dampers will be presented.

INTRODUCTION

During the installation of offshore wind turbines, the piling noise of hydraulic impact hammers induce considerable underwater sound emissions. Peak sound pressure levels have been measured high above 190 dB re 1 µPa at a distance of 750 m from the pile driver. This construction noise is potentially harmful to marine life, in particular to marine mammals. In addition, this noise induces flee reactions over a large area (about several kilometers), since water is a very efficient conductor of sound.

Different zones of underwater noise emissions can be defined in the surrounding of an acoustic noise source [1].

Within the zone of audibility 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, underwater noise can induce temporary (TTS) or permanent (PTS) threshold shift. Important acoustic information like communication might be masked caused by reductions in hearing sensitivity of an animal.

Close to a very loud source of noise, like 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), must be avoided.

Due to larger piles requiring higher driving energies, even higher underwater noise levels are expected in future offshore projects. Moreover, an increasing number of erected offshore wind turbines might aggravate this problem.

Hence, effective noise reducing methods are in great demand to keep the limiting level of 160 dB (SEL) at a distance of 750m from offshore pile driving, as established by the German Authority BSH.

The mitigation of underwater noise is necessary, getting sound levels below recommended acoustic emission thresholds that are no longer harmful and disturbing to marine mammals and other protected animals.

RAM NOISE SPECTRA

Piling, in particular using hydraulic hammers creates high frequency noise with considerable underwater sound levels [1]. Depending on the type of offshore foundations, hydraulic hammers are used to drive piles and monopiles of up to 400 tons between 30 m and 40 m into the sea ground.

The short impact pulse of the hammer induces an impact wave in the pile, traveling through the pile into the ground, with reflections at the ends of the pile. It also induces a sound wave in the surrounding water with an impact pressure of about 10-30 bar. This radiated underwater noise is propagating into all directions with a speed of sound of about 1500 m/s.

Underwater noise is usually described by two sound levels expressed in decibels (dB). The first level is the peak level (L_{peak}) which depends on the maximum instantaneous positive or negative sound pressure $|p_{peak}|$ measured and on the reference underwater sound pressure, $p_0 = 1\mu Pa$, as presented in equation 1.

$$L_{peak} = 20\log\left(\frac{|p_{peak}|}{p_0}\right) \text{ in dB re: } 1\mu\text{Pa.} \qquad \text{(eq 1)}$$

The second level used for describing pile driving underwater noise is the sound exposure level (L_E) in decibels (e.g.,dB re:$1\mu Pa^2 s$), also abbreviated SEL, which is an equivalent energy level of the noise during T_1 and T_2 of a single pile driving impulse based on $T_0 = 1s$ (see equation 2).

$$L_E = 10\log\left(\frac{1}{T_0}\int_{T1}^{T2}\frac{p(t)^2}{p_0^2}dt\right) \text{ in dB re: } 1\mu\text{Pa}^2\text{s.} \qquad \text{(eq 2)}$$

The SEL is the level of a continuous sound with 1s duration and the same sound energy as the pile driving impulse.

In Figure 1, spectral information of pile strokes are given by third octave spectra of the sound exposure levels SEL for three different hydraulic hammers.

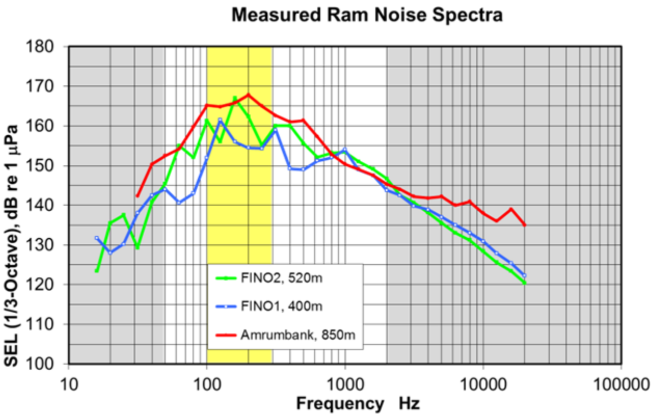

Figure 1: Pile driving noise spectrum, [2].

The highest spectral levels of the measured underwater ram noise for different hammers are shown in the low frequency range, from 100 to 300 Hz. These spectral levels are responsible for the high broadband level of piling noise. Therefore, they have to be reduced using effective noise mitigation systems to meet with the allowable SEL established by the BSH.

AIR BUBBLE CURTAINS (ABC)

A curtain of small air bubbles in the water, released at the bottom of the seabed, rising up to the water surface and placed around the noise source, can reduce the underwater sound propagation by scattering, multiple reflections of traveling acoustic waves and dissipation of resonant vibrating air bubbles.

In Germany, first offshore applications of air bubble curtains achieved noise reductions of 10-13 dB during pile driving operations of the offshore platforms FINO3 and "alpha-ventus" in the North Sea, [2].

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 and the bubble distribution, and the influence of the tide current of the sea, together with slow ascent rates of the bubbles.

Figure 2 shows that the air bubble curtain attenuation of high frequency noise, above 1 kHz, is very high. However, the sound level of the piling noise mainly depends on the lower frequency noise, far below 1 kHz, where the attenuation from bubble curtain is only poor. The reasons for this is that large air bubbles (several cm in diameter) with low resonant frequencies are uncontrolled, showing chaotic movements and dividing themselves when they are slowly arising to the surface of the water as can be observed in Figure 3.

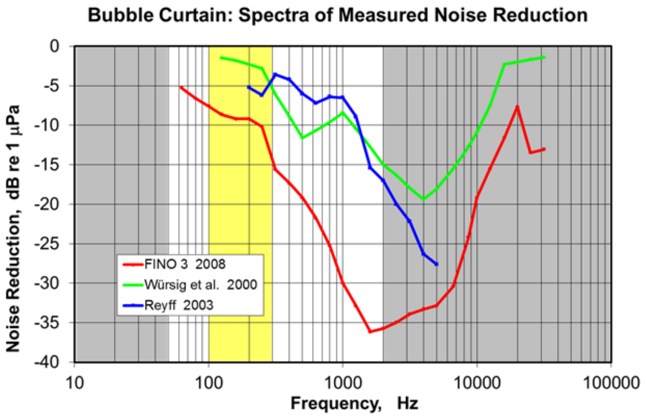

Figure 2: Noise reduction spectra of bubble curtains, [2].

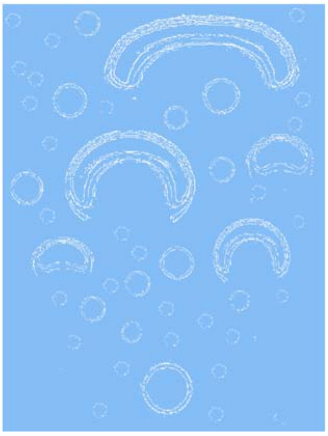

Figure 3: Uncontrolled chaotic movement of free air bubbles in water, slowly arising to the surface and dividing themselves

Against this, only constant shapes of air bubbles and nearly steady state resonant excitation are able to achieve high sound attenuation of resonant air bubbles.

As a consequence, there is no benefit from high theoretical underwater sound attenuation potential of large air bubbles with low resonant frequencies, when using conventional air bubble curtains.

As shown in Figure 2 the attenuation of high frequency noise is very high above 1 kHz, but only poor below 1 kHz.

NEW HYDRO SOUND DAMPERS (HSD)

To overcome the disadvantages of the ABC, a new underwater noise reducing method is developed, using gas filled envelope bodies as hydro sound dampers, instead of free natural air bubbles, similar to elastic balloons [3]. A patent has been granted.

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 4 shows three HSD offshore configurations: (a) staggered HSD-grid, (b) large fishing net round a pile and, (c) a telescopic frame covered with HSD elements.

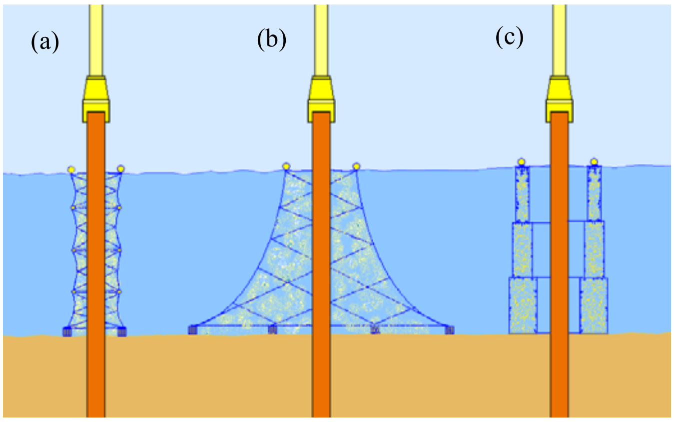

Figure 4: (a) Staggered HSD-net, (b) large fishing net and, (c) telescopic frames, [3]

Systems of hydro sound dampers can also be fixed below a ram or a piling frame as observed in Figure 5. Another HSD offshore application is to cover an extensive area of the sea floor around the pile to reduce the indirect noise transmitted from the ground into the water (Figure 5c).

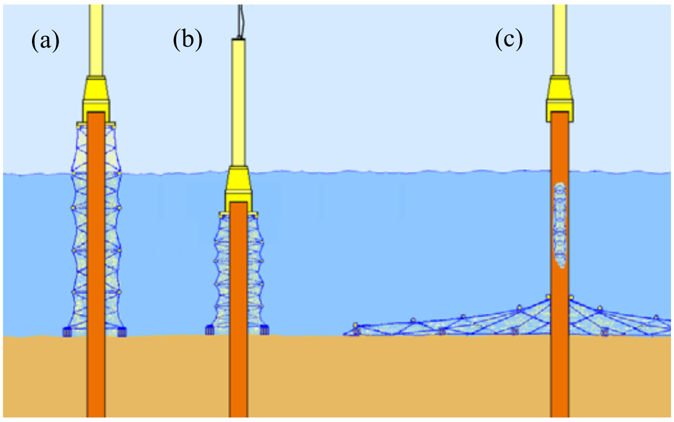

Figure 5: HSD-net (a) fixed to a ram, (b) fixed to a piling frame or, (c) covering the ground, [3]

The HSD-system of Fig. 6 is a donut-like container, enclosing the HSD-net. It can be fixed below a piling frame, or below the hydraulic ram or it can be swimming round the pile as shown in Fig. 6.

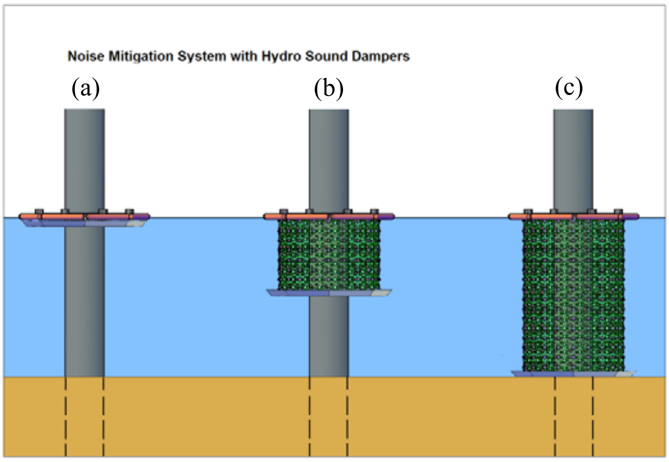

Figure 6: Swimming noise mitigation HSD-system as a donut-like container, enclosing the HSD-net: (a) closed, (b) unfolding and, (c) fully unfolded HSD-system, [7]

It only needs a very short time to unfold the system. This is done by let the heavy weight of the HSD-net falling down or winding it up after Fig. 6. HSD-systems are independent of compressed air, not influenced by the tide current of the sea and they are easy adaptable to different applications.

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.
In contrast to free air bubbles of conventional air bubble curtains, hydro sound dampers allow to use three different physical reasons for effective underwater noise attenuation:

- Resonant effects of air filled small latex balloons in water increase the scattering and extinction cross sections of the vibrating balloons by a factor of 1000 and more compared to the physical cross section, thus reducing underwater sound up to 35 dB and more as it is known from small air bubbles in water. The resonance frequency of an air filled latex balloon in water is adjustable, even to low frequency ranges, in contrast to free air bubbles, and it is inversely proportional to the diameter of a balloon. It is also depending on the gas pressure inside, the water depth and the stiffness of the envelope material. The resonant effect is of course frequency dependent and a very effective noise mitigation method near the resonance frequency of a balloon.

- Dissipation and material damping effects according to the material damping potential of the envelope material and the filling material inside the vibrating balloons. Maximum damping is obtained near the resonant frequency of a damped balloon, achieving noise reductions between 10 and 30 dB (SEL).

- Reflections of sound waves at impedance steps, as air filled balloons in water increase the compressibility of the mixed water-body, decrease the bulk modulus of the mixture and decrease the sound speed and the specific impedance of the mixture very much. There are sound reflections at the transition from original water to the water volume, filled with HSD-balloons of about 1 – 2 % volume rates, resulting in noise reductions between 5 and 15 dB (SEL). This effect of changing the material property of the surrounding water is not frequency dependent.

The important resonant effect with high scattering, multiple reflections and effective absorption of sound waves in the water is to be seen in Fig.7. The very strong interaction of a vibrating HSD-element and the surrounding water can be seen at the water surface in Fig.7. This interaction also takes place under water, but it is not visible in this image.

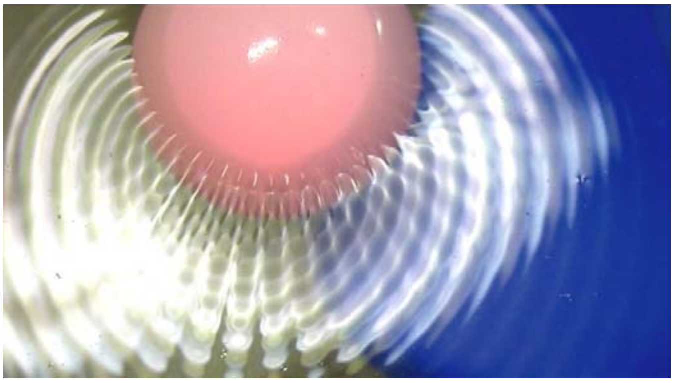

Figure 7: Scattering, radiation and strong interaction of a vibrating HSD, [4]

Hydro sound dampers are used in the whole frequency range of pile driving noise from 50 - 5000 Hz. It is possible to control the damping rate, the size, the number and the distribution of the HSD around the pile. Finally, HSD don't need a supply of compressed air.

NUMERICAL SIMULATION OF HSD NOISE REDUCTION

The underlying system in Fig. 8 of numerical simulations of HSD noise reductions is a vertical section of about 10m x 22.5m of the surrounding water of an offshore pile, placed 12.5m outside the section at the left side of the system (not to be seen).

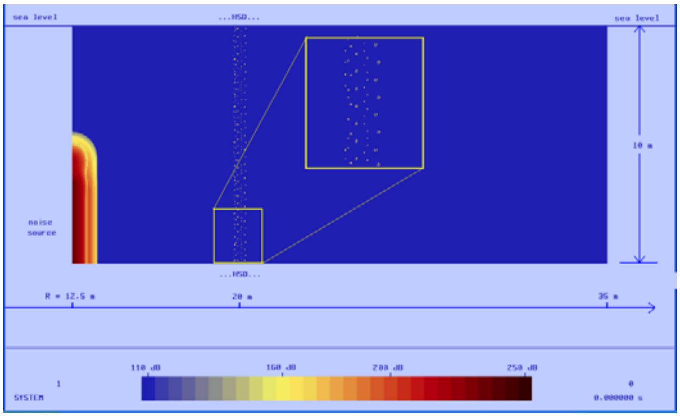

Figure 8: Numerical System, sound wave and HSD-elements [3].

The impact of a hydraulic hammer induces a sound wave during piling, traveling to the right side of the system. This sound wave function was measured during pile driving of an offshore foundation in the North Sea.

Within the numerical example, the traveling sound wave of the system is freezed at the time step t = 0.0122s in Fig. 9 showing the distribution of the actual hydro sound pressure levels L_p of the instantaneous sound pressure at this time.

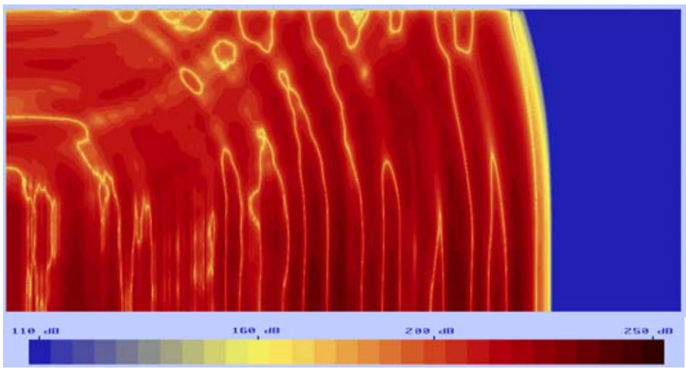

Figure 9: Distribution of sound pressure level LP (dB), [3].

Using small HSD distributed near a vertical line, a mean reduction of sound pressure levels L_p up to 30 dB is obtained behind this line of hydro sound dampers, as shown in Fig. 10. Even the scattering, reflections and interference of different sound waves radiated from the vibrating elements of hydro sound dampers can be observed in this Figure behind the line of HSD at the right side.

There is an typical increase of the sound pressure levels L_p at the left side of the barrier of hydro sound dampers in Fig. 10 according to reflections of sound waves at the impedance step, as air filled HSD-balloons in water increase the compressibility of the mixed water-body and decrease the specific impedance of the mixture.

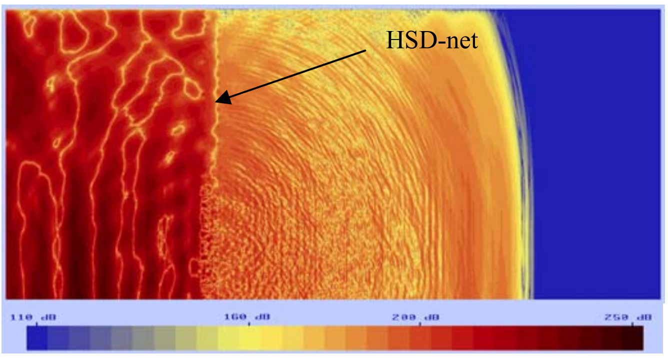

Figure 10: SPL noise reduction up to 30 dB, using HSD, [3].

Fig. 11 shows the distribution of the sound exposure levels SEL at all positions of the system calculated and summarized up to the same time of t = 0.0122s, without using hydro sound dampers.

The SEL is an equivalent energy level of the accumulated noise energy of a single pile driving impulse, comparable to the level of a continuous sound with 1s duration and the same sound energy as the pile driving impulse.
So the maximum SEL levels are only reached at the end of a pile driving impulse.

There is a simulated noise reduction of the sound exposure levels SEL between 23 to 30 dB on the right side in Fig. 12, resulting from scattering, reflections and absorption of sound waves by the barrier of hydro sound damper elements near a vertical line. There are also effects of increasing SEL levels on the left side from wave reflections.

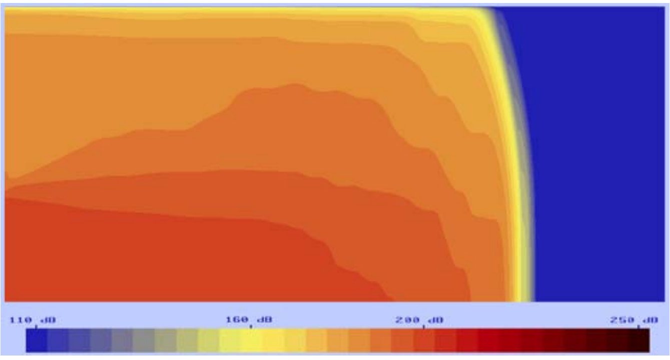

Figure 11: Distribution of sound exposure levels SEL, [3].

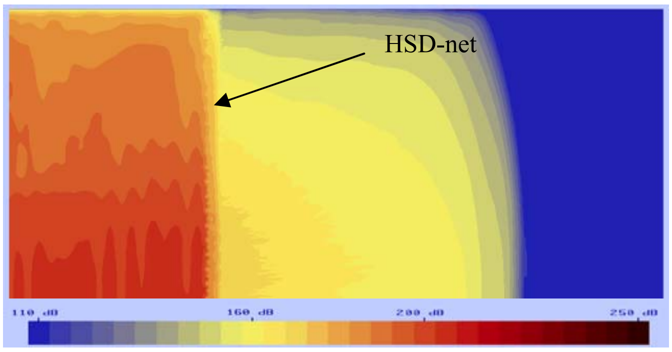

Figure 12: SEL noise reductions up to 23-30 dB, using HSD-elements, [3].

The obtained reduction of noise mainly depends on the number, the sizes and the damping rates of the HSD elements.
All different types of HSD elements are tuned to several different resonant frequencies to cover the whole frequency range of the piling noise. It is also possible to tune HSD elements of the same size to different resonant frequencies. The effect of noise reduction is increased near the resonant frequency of a HSD within a frequency range of more than one octave as to be seen in the simulated spectrum of Fig. 13.

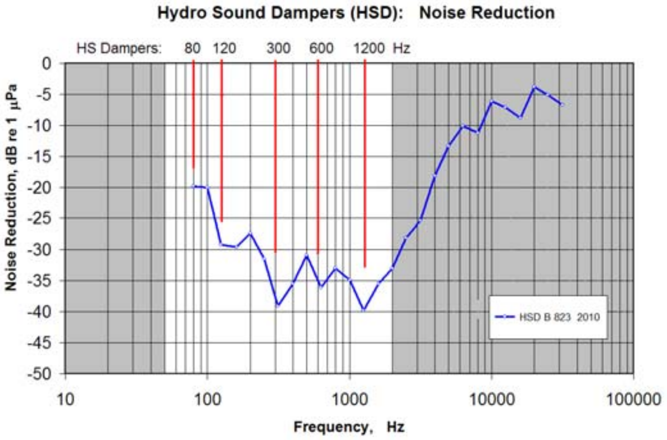

Figure 13: Simulated mitigation spectrum of hydro sound dampers, [3].

To get sufficient noise mitigation within the most important frequency range of piling noise, only 5 different HSD-types are used after Fig. 13, tuned to different resonant frequencies between 80-1200 Hz.

MEASURED NOISE REDUCTION OF HSD

Experimental tests and measured results confirm the high underwater sound attenuation potential of hydro sound dampers.

The first experiment is a small laboratory model of a ram pile, 10cm of diameter, using the impact of a dropped weight [5]. Two different noise mitigation methods are used: The reduction of an air bubble curtain is compared to hydro sound dampers.

The results of the measured noise reductions are summarized in the Tab.1

Table 1: Measured noise reductions of a laboratory pile model, [5]

Laboratory pile model, impact:		
Measured noise reduction	**L_{peak}**	**SEL**
Air bubble curtain (ABC)	21 – 28 dB	10 – 16 dB
Hydro sound dampers (HSD)	19 – 22 dB	15 – 22 dB

For the second experiment the large wave flume “Großer Wellenkanal, GWK” in Hannover, with a length of 300m, is used as a model of realistic sound radiation, comparable to the free radiation of offshore sites. Fig. 14 shows the HSD-net with small HSD-balloons of diameters between 5 – 6 cm in the large wave flume GWK.

Figure 14: HSD-net with small balloons in the water canal, [6]

The small HSD-balloons are fixed to the net at distances of 15 to 30 cm, covering about 8-10% of the net surface.
All balloons were tuned to resonant frequencies only between 200 and 300 Hz. This is about the decisive frequency range of piling noise after Fig. 1 and it is advantageous to get high noise reductions within this frequency range.

Conventional air bubble curtains are not very effective in this decisive lower frequency range after Fig. 2, as free air bubbles in water, with diameters of several centimeters, are not stable after Fig. 3.

The measured results of underwater noise reduction of the small HSD-balloons in the large wave flume with sweep excitation between 100 Hz and 3000 Hz are summarized in Tab. 2.

Table 2: Measured noise reductions in large wave flume GWK, [7]

GWK model, sweep excitation:

Measured noise reduction:	L_{peak}	**SEL**
Hydro sound dampers, (broadband)	19 dB	20 – 22 dB
Hydro sound dampers, (betw.: 200 – 300 Hz)		20 – 30 dB

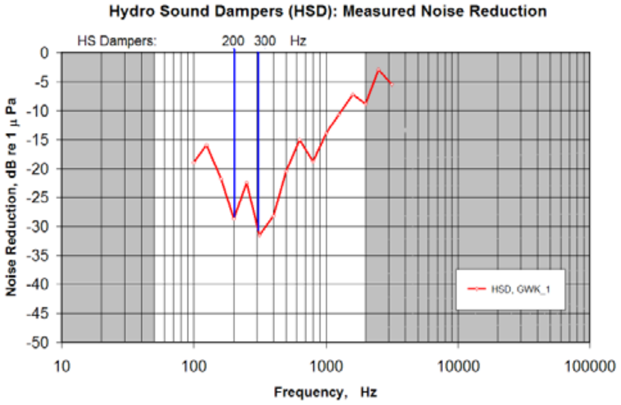

Figure 15: Measured noise reduction up to 30 dB (SEL), [7]

The very high noise reductions up to 30 dB (SEL) in the lower frequency range between 200 and 300 Hz of the measured noise reduction spectrum after Fig. 15. of course depend on the small tuned HSD-balloons.

This result is very interesting, as the used HSD-net is only covered by HSD-elements at about 8-10% of the net surface. Thus, the measured results show, that it is possible to realize a screen of more than 90% permeability to current water, but impermeable to under water noise with up to 30 dB reduction of noise.

This result is very remarkable as it is well known from acoustics and sound isolations, that already a small opening of 5-10% of the isolating surface breaks down the whole effect of sound isolation. The opening of the HSD-net is more than 90% of the net surface, the net is nearly free permeable, but reduces the sound level in a certain frequency range up to 30 dB. The sound energy is reduced to only 1 pars pro mille.

SUMMARY

During the construction of offshore wind turbines the use of hydraulic impact hammers induces considerable underwater sound emissions. Effective noise reducing methods are necessary to keep the limiting level of 160 dB (SEL) at a distance of 750 m from pile driving of the German Authority BSH.

Air bubble curtains as the first used noise mitigation systems are very expensive, they only achieve poor sound attenuation in the decisive frequency range below 1 kHz, and they are strongly influenced by the tide current of the sea.

The new underwater noise reducing method of hydro sound dampers (HSD), presented in this paper overcome these problems. Gas filled envelope bodies similar to elastic ballons are used instead of free natural air bubbles. Resonance effects, scattering and dissipation of the hydro sound dampers (HSD) reduce the noise transmissions in a very effective way. The size, the damping rate, the distribution and the effective frequency range of the hydro sound dampers can be fully controlled, if the envelope bodies are fixed to pile surrounding fishing nets or to frames. These HSD-nets are enclosed in a donut-like container, fixed to a piling frame, or below the hydraulic ram or swimming round the pile. It needs a very short time, just falling down the HSD-net or winding it up.

HSD-systems are independent of compressed air, not influenced by the tide current and they are easy adaptable to different applications.

The theoretical background of the new method and technical realizations are discussed in the paper. Furthermore, numerical simulations with broadband noise reductions between 23 - 30 dB (SEL) are shown and compared to experimental results of up to 30 dB (SEL) measured mitigations of underwater noise.

ACKNOWLEDGMENTS

The measurements presented in this contribution were carried out by the Technische Universität Braunschweig (IGB-TUBS) and are funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) within the research project FKZ 0325365. The authors greatly acknowledges the financial support of the BMU.

The theory and the numerical simulations presented in this contribution are carried out by Dr. Karl-Heinz Elmer.

The Hydro Sound Dampers are applied for international patents.

REFERENCES

[1] Elmer, K.-H.; Betke, K; Neumann, T.; (2007): Standard Procedures for the Determination and Assessm. of Noise Impact on Sea Life by OWF, BMU final report 0329947, www.naturschutzstandards-erneuerbarer-energien.de/images/literatur/2007_Elmer_Schall 2_Offshore-Wind.pdf

[2] Betke, K.: (2008) Minderung von Unterwassergeräuschen beim Bau von Offshore-WEA, BSH-Workshop FINO3, Hamburg, 8. Oct. 2008.

[3] Elmer, K.-H.: (2010) Pile driving noise reduction using new hydro sound dampers, BSH-workshop on pile driving, ESC2010, Stralsund, March 21, 2010. www.bsh.de/de/Das_BSH/Veranstaltungen/Cetacean_Society/Elmer.pdf

[4] Elmer, K.-H.: (2010) New hydro sound dampers to reduce underwater pile driving noise emissions, Internat. Conf. DEWEK2010, Bremen, 17-18 Nov. 2010[5] Branz, K.N.: (2010) Experimentelle Versuche zur Hydroschalldämmung bei der Rammung von Offshore-Gründungsstrukt.; Bachelor Thesis, Inst. f. Grundbau und Bodenmechanik, TU Braunschweig

[6] Elmer, K.-H.; Gattermann, J.; Fischer, J.; Bruns, B.; Kuhn, C.; Stahlmann, J.: (2011): Hydroschalldämpfer zur Reduktion von Unterwasserschall bei Offshore-Gründungen; Pfahlsymposium 2011, Braunschweig, 17.-18. Februar 2011; Mitteilungen des Instituts für Grundbau und Bodenmechanik, (J. Stahlmann), TU Braunschweig, Heft 94, 2011

[7] Elmer, K.-H.; Gattermann, J.; Bruns, B.; Kuhn, C.; Stahlmann, J.: (2011): Mitigation of underwater piling noise using new hydro sound dampers (HSD); 8th International Symposium of "Field measurements in geomechanics (FMGM)" 2011, 12.-16. September 2011, Berlin, 2011