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Offshore Wind Farm noise emission: impacts on marine life

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Adriatic IPA
Cross Border Cooperation 2007 2013

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- **Offshore wind farm life-cycle and noise sources**
- **Pre-existing noise and background noise**
- **Choice of the propagation model**

- **Receptors sensitivity**
- **Threshold levels for biological effects**
  - *Marine mammals*
  - *Fish*
- **Impact zones, known and potential effect**

- **Best practices**
- **Mitigation procedures**

Offshore wind farm life-cycle and noise sources

1 Pre-Construction (1-5 years)
2 Construction (around 1 year)
3 Operation (20-25 years)
4 Decommissioning or Repowering (around 1 year)

1

- Air Gun
- Impact Pile Driving
- Shipping Traffic
- Drilling

2

- Dredging, rock laying, trenching,
- Impact Pile Driving
- Turbine structure installation noise, diver tools
- Shipping Traffic

3

- Wind turbine operational noise
- Shipping Traffic

4

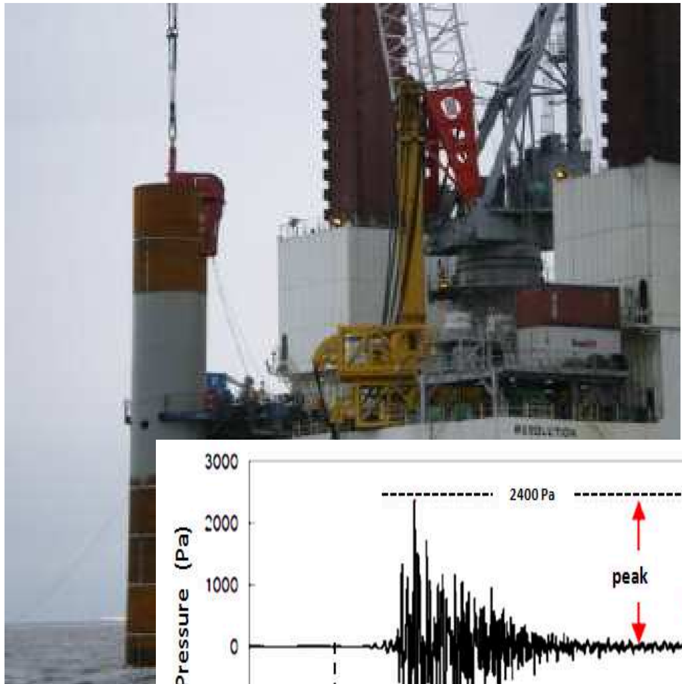
- Blast /explosion
- Same noise sources of construction phase

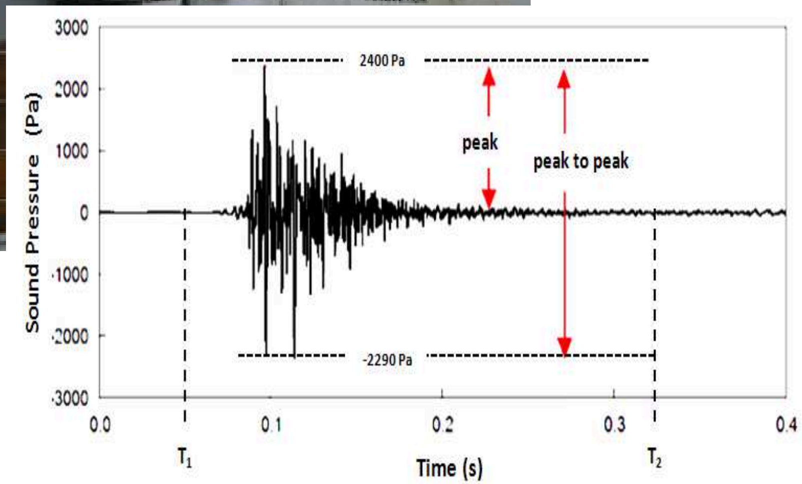
Offshore wind farm noise
Pre-Construction / Construction noise

Source	Source Level [dB re. 1 µPa 1m]	Unit	Frequency Range [Hz]	Major Amplitude Range [Hz]	Duration [ms] /Type of noise
Impact Pile Driving	190-250	SPL RMS	20 -20000	100 -500	Impulsive 50/100 ms
	230 peak / 243-257 peak to peak	SPL			
Vibro Driving	160-190	SPL RMS	20 -20000	< 2000	Continuous
Drilling	145-190	SPL RMS	10 - 10000	< 100	Continuous
Dradging	168 - 188	SPL RMS	30- 20000	100 - 500	Continuous
Rock Laying	whithin background noise				Continuous
Shipping	150 - 190	SPL	function of ship type		Continuous

Offshore wind farm noise
Pre-Construction / Construction noise

Pile Driving





Sound Pressure of a single typical impulse pile drive noise (Nehls et al 2007)

- <u>impulsive noise source</u>:

between 50 and 100 ms, 30-60 beats per minute

- <u>very high sound pressure levels:</u>

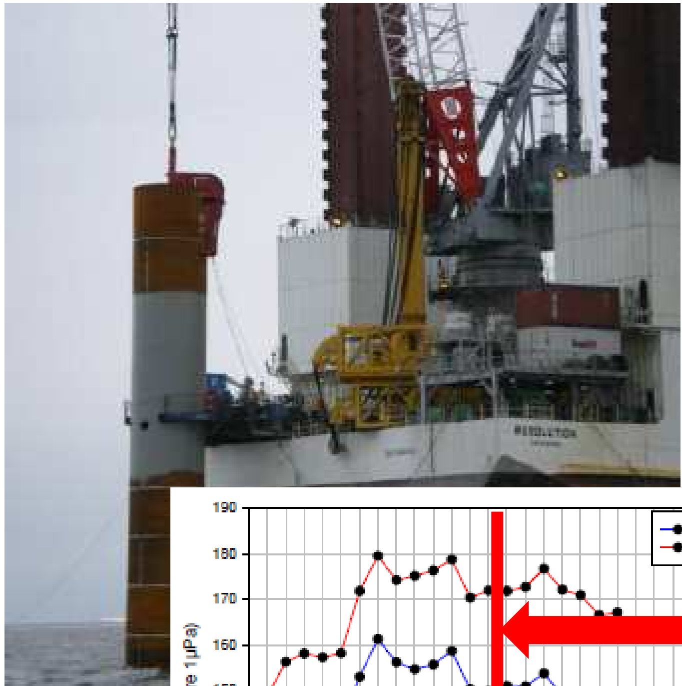
≈ **peak 190-260 dB** *re 1 μPa SL(1m)*

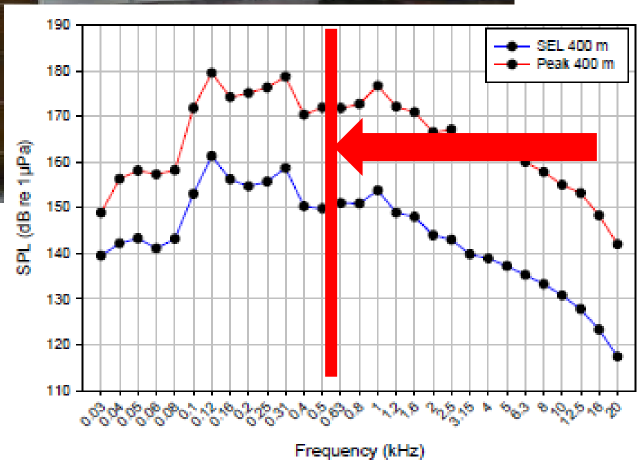
≈ **SEL 170-225 dB** *re 1 μPa²s SL(1m)*

- <u>several hundred strikes per pile</u>

Offshore wind farm noise
Pre-Construction / Construction noise

Pile Driving





- impulsive noise source:

between 50 and 100 ms, 30-60 beats per minute

- very high sound pressure levels:

≈ **peak 190-260 dB** *re 1 µPa SL(1m)*

≈ **SEL 170-225 dB** *re 1 µPa²s SL(1m)*

- several hundred strikes per pile
- broad band noise
- main energy at lower frequencies

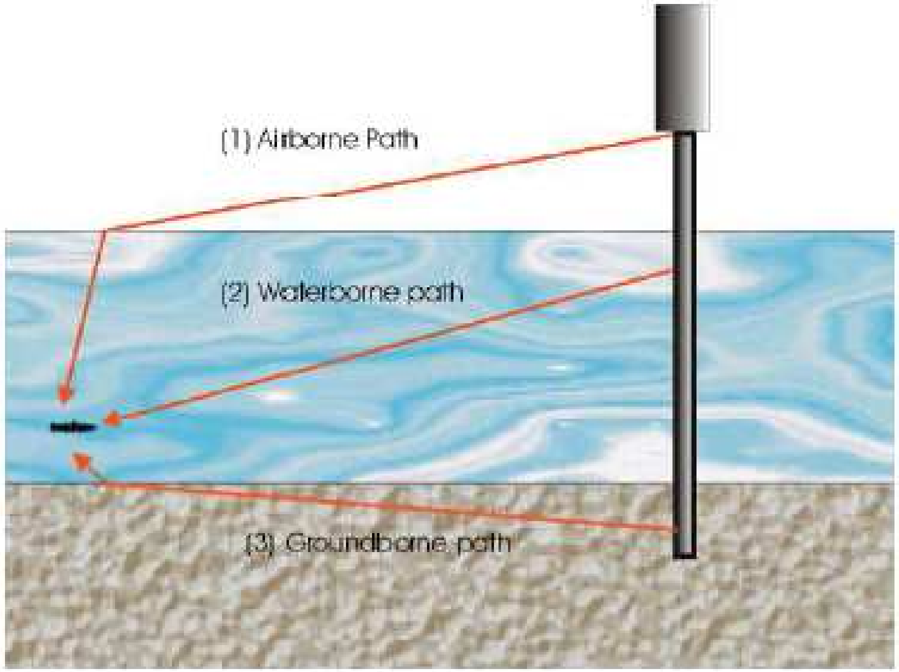
< 1000 Hz (maxima < 300 Hz)

Offshore wind farm noise
Pre-Construction / Construction noise

Pile Driving

Source output depends on:

- hammer energy
- *sea bed penetration*
- *sea bed and sediment properties*
- *pile dimensions*
- *water depth …*



Received level depends on transmission loss variation:

- *bathymetry, …*
- *fluctuations in environmental conditions (sea state …)*

Offshore wind farm noise
Pre-Construction / Construction noise

Pile Driving

Park	Pile diameter [m]	Measuring distance [m]	Peak Level [dB re. 1 µPa]	SEL [dB re. 1 µPa²s]	References
Fino 1, Germany	1.6	750	192	162	Ainslie et al. 2009
Fino 2, Germany	3.3	530	190	170	Ainslie et al. 2009
Amrunbank West, Germany	3.5	850	196	174	Ainslie et al. 2009
Q7 Park, Netherlands	4	890 - 1200	195	172	Ainslie et al. 2009
Utgrunden	3	30	203	184	ØDS. 2000
		320	183		
North Hoyle	4	955	192		Nedwell et al. 2004
		1881	185		
Horns Rev	4	230	185		Tougaard et al 2008
		930	178		

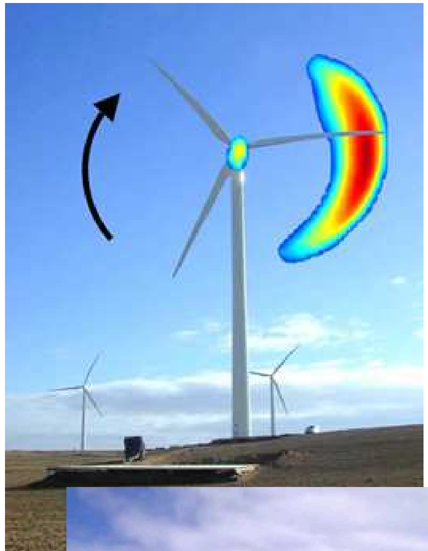
Offshore wind farm noise
Operational noise

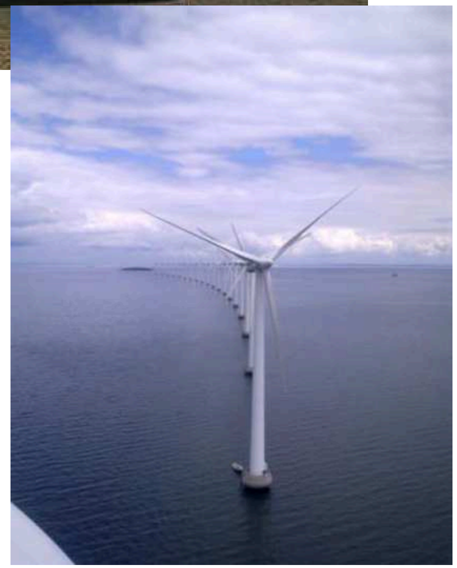
Continuous noise radiated during operation

Noise from wind turbines comes in two forms:

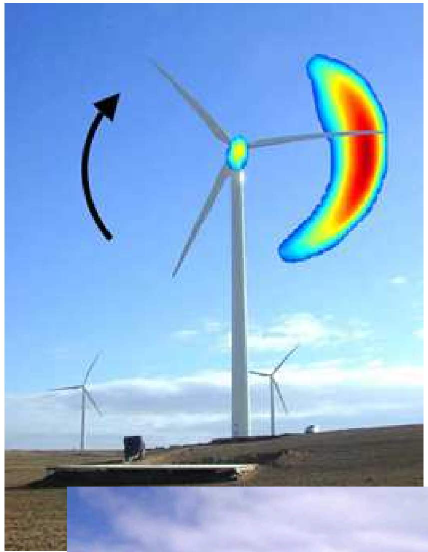
- **<u>Mechanical noise</u>** associated with machinery housed in the nacelle turbine:
  - ✓ imbalances of the rotating components,
  - ✓ the teeth in the gearbox coming into contact with each other (referred to as gear meshing)
  - ✓ electro-magnetic (E-M) interaction between the spinning poles and stationary stators in the generator

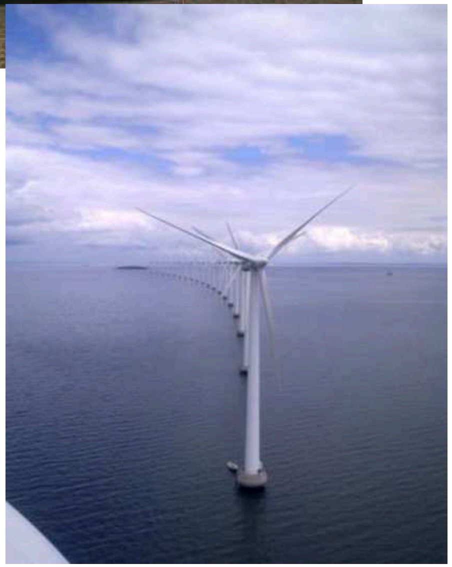
- **<u>Aerodynamic noise</u>** associated with the interaction of turbulence with the blade surface:
  - ✓ low-frequency noise,
  - ✓ inflow turbulence noise
  - ✓ airfoil self-noise





Offshore wind farm noise
Operational noise





Mechanical noise has a two different propagation paths:

- airborne path
- strong structural path between the drive train (where the vibration is created), through the nacelle support frame, tower, into the foundation and finally from the foundation into the surrounding water where it is released as noise.

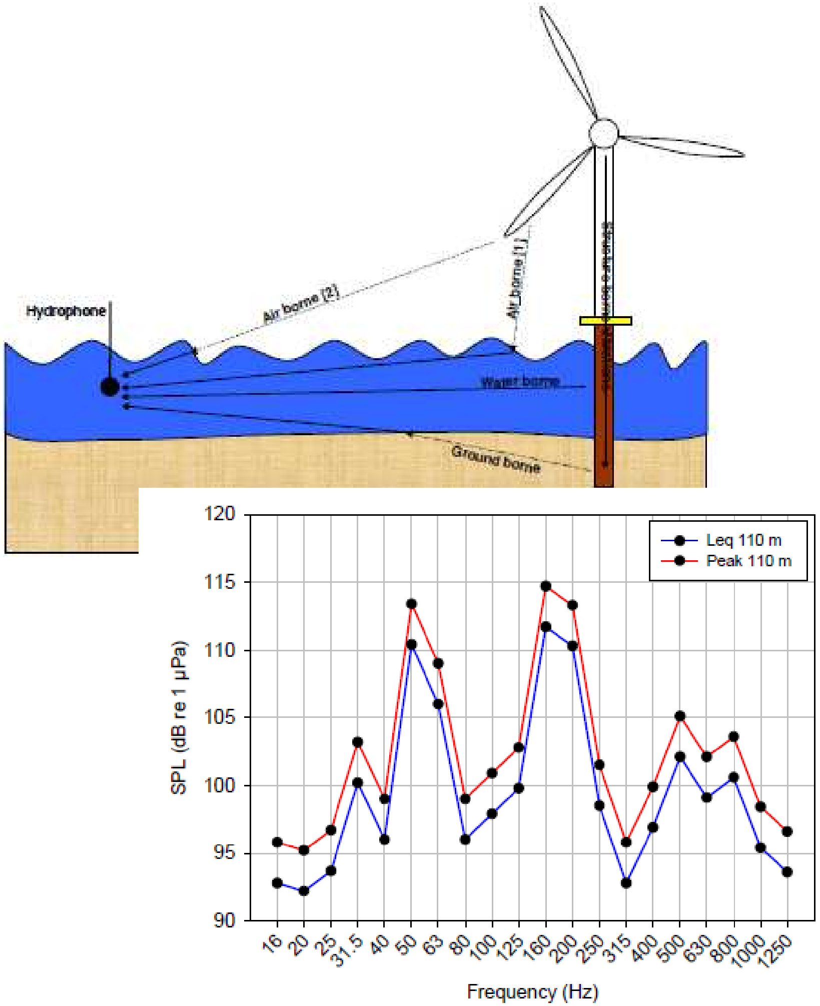
Aerodynamic noise :

- Pass through the air, *which may also enter the water via an airborne path. Aerodynamic noise will increase with increasing rotational velocity of the turbine.*

NB. The movement of air over the whole structure including the turbine blades and the hydrodynamic forces from passing waves will induce structural vibrations.

Offshore wind farm noise
Operational noise

Underwater noise



- operational noise will occur over a number of years (20/25 years)
- depends on turbine operation – wind speed
- much lower intensity than the noise produced during construction phase

≈ **SEL 110-180 dB** *re 1 µPa²s SL(1m)*

- the sound intensity is dominated by pure tones,, with frequencies mostly below 700 Hz
- low frequency noise during operation

Offshore wind farm noise
Operational noise

Underwater noise

Park	Foundation Type	Power [MW]	Wind Speed [m/s]	Distance [m]	Frequency [Hz]	Received Noise Level
Nogersund	Tripod	0.2	12	100	16	113 dB re. 1 μPa
Vindeby	Concrete Gravity Base	0.5	13	14	150	100 dB re. 1 $\mu Pa^2/Hz$
Bockstigen	Monopile	0.6	13	20	160	95 dB re. 1 $\mu Pa^2/Hz$
Middlegrunden	Concrete Gravity Base	2	13	Converted to SL (1m)	125	115 dB re. 1 $\mu Pa^2/Hz$
Utgrunden	Monopile	1.5	13	Converted to SL (1m)	180	151 dB re. 1 μPa
Utgrunden	Monopile	1.5	12	110	160	115 dB re. 1 μPa
UK	Monopile	3-3,6	3,9 -7,2	20	100	112 dB re. 1 $\mu Pa^2/Hz$

Operational noise measurements (reproduced from Marmo et al. (2013)), maximum noise levels recorded with their corresponding frequencies

Pre-existing noise and background noise

Ambient noise is sound that is always present and cannot be attributed to an identifiable localised source.

Well understood for deep ocean water
In shallow water (<200m) ambient noise is less well understood and extremely variable.

Background noise The combination of ambient noise, which cannot be attributed to a particular source, and identifiable local sources is termed background noise. This is all the noise received at a particular time and location that is in addition to the source of interest.

*In shallow costal water, overall unweighted sound pressure level (SPL_{RMS}) are generally between **85 and 120 dB** re 1 μPa* with a sound power spectrum that shows main energies below 1000 HZ.

NB: an assessment of the background noise is essential for a valid assessment of the potential for effect from the introduction of a wind farm

Choice of the propagation model

Sound propagation model in shallow water

RL = SL - TL

RL = receiving level
SL = source level
TL = transmission loss

Sound amplitude dies away at greater range because of Transmission Loss due to:

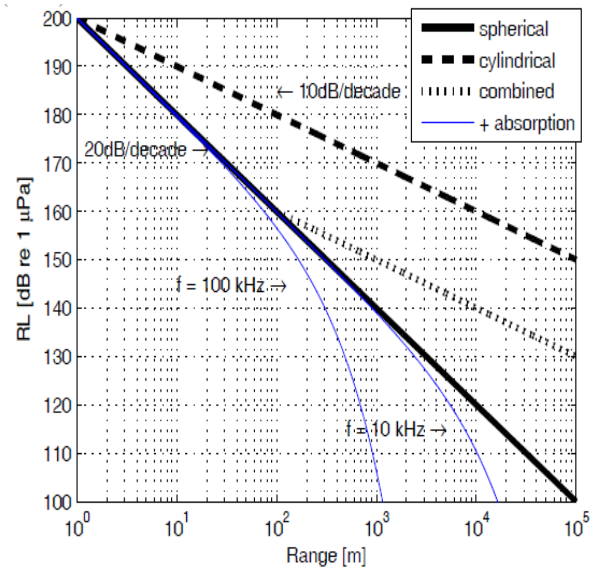
•**Spreading**

•**Absorption**

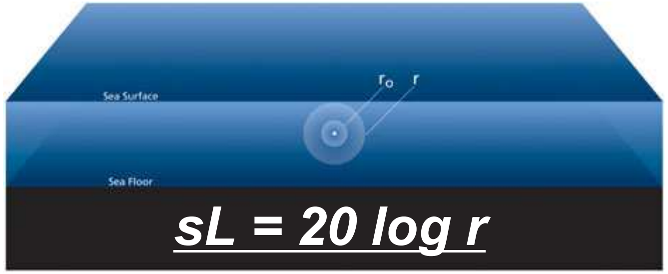
(frequency dependent)

•**Interaction with boundaries**

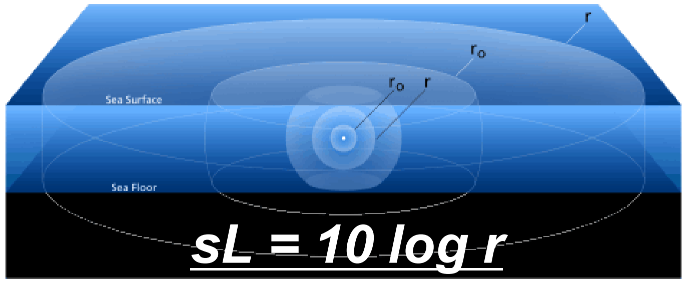
(seafloor, seabed)



Spherical propagation



Cilindrical propagation



Choice of the propagation model

Sound propagation model in shallow water

- Propagation model needed
- Why is important to determine Source Level?

  - *to compare acoustic output of sources*

  - *to propagate sound outward to determine impact zones*

✓ great variety of propagation models available: ray tracing, normal mode, parabolic equation, wavenumber integration

✓ the forecast quality essentially depends on the accuracy of the input data and of the model used.

Impact on marine life

Theoretical zones of noise influence

Marine Mammals

Richardson et al. (1995) define *four zones* of noise influences:

•**the zone of *audibility*** is defined as the area within which the animal is able to detect the sound.

•**the zone of *masking*** *is* the region within which noise is strong enough to interfere with detection of other sounds, such as communication signals or echolocation clicks.

•**the zone of *responsiveness*** is the region in which the animal reacts behaviorally or physiologically. This zone is usually smaller than the zone of audibility.

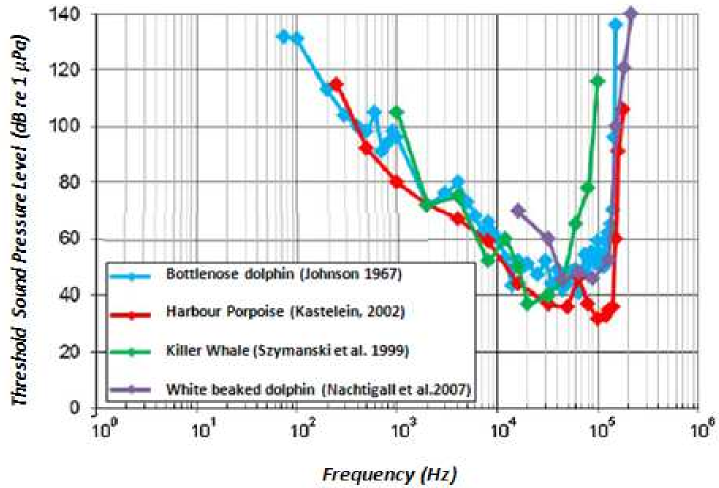
•**the zone of *hearing loss*** is the area near the noise source where the received sound level is high enough to cause tissue damage resulting in either temporary threshold shift (TTS) or permanent threshold shift (PTS) or even more severe damage (injury**).**

Hearing in marine mammals

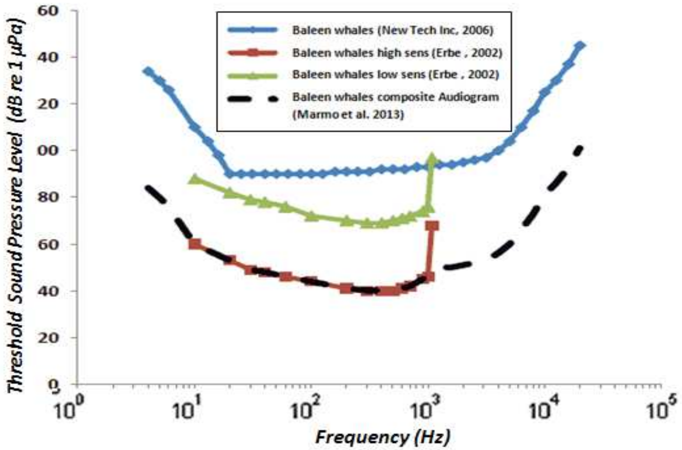
Hearing thresholds/ Audiograms

Hearing studies on marine mammals are conducted in three different ways:
•*behavioral studies*
•*electro-physiological studies*
•*anatomical studies*.

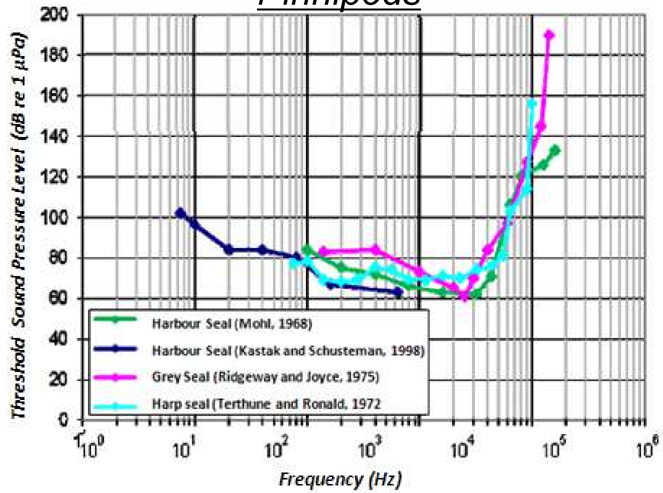
Odontocetes



Mysticetes



Pinnipeds



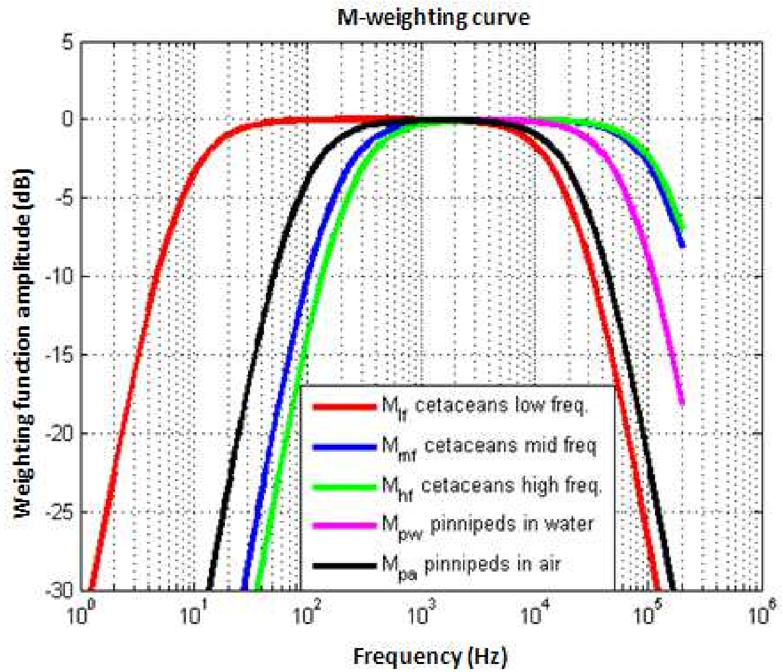
Hearing in marine mammals

dB$_{ht}$ metric

The dBht(Species) provides a measurement of sound that allows the comparison of the effects of noise on a wide range of species. The loudness of a sound for a given species may be assessed by passing the sound through a filter defined in terms of the measured hearing threshold of the animal (audiogram).

Marine mammal auditory weighting functions

Sauthal et al. (2007) proposed the use of weighting functions, to filter underwater noise data to better represent the levels of underwater noise which various marine species are likely to be able to hear.
Cetaceans and pinnipeds were divided into five functional hearing groups.



“M-weighting” functions reproduced from Southall et al.(2007)

Criteria and threshold levels for biological effects on marine mammals

Hearing loss / Injury
PTS Criteria

Species	Exposure limit	unit	Source/ Type of Sound	Reference
Hf, LF, MF	230 dB re. 1 µPa (peak)	SPL	Single Pulse /	after Sauthall
Cetaceans	198 dB re. 1 µPa^2 s (M)	SEL	Multiple Pulse	et al. 2007
Pinnipeds	218 dB re. 1 µPa (peak)	SPL	Single Pulse /	after Sauthall
(in water)	186 dB re. 1 µPa^2 s (M)	SEL	Multiple Pulse	et al. 2007
Hf, LF, MF	230 dB re. 1 µPa (peak)	SPL	Non pulse	after Sauthall
Cetaceans	215 dB re. 1 µPa^2 (M)	SEL		et al. 2007
Pinnipeds	218 dB re. 1 µPa (peak)	SPL	Non pulse	after Sauthall
(in water)	203 dB re. 1 µPa^2 s (M)	SEL		et al. 2007
Harbour porpoise	200 dB re. 1 µPa (peak)	SPL		after Toungard
	180 dB re. 1 µPa^2 (M)	SEL		2013
LF, MF	230 dB re. 1 µPa (peak)	SPL	Impulsive	after NMFS
Cetaceans	187 dB re. 1 µPa^2 s (M)	SELCUM		2013
HF	201 dB re. 1 µPa (peak)	SPL	Impulsive	after NMFS
Cetaceans	161 dB re. 1 µPa^2 s (M)	SELCUM		2013
Phocid	235 dB re. 1 µPa (peak)	SPL	Impulsive	after NMFS
Pinnipeds (in water)	192 dB re. 1 µPa^2 s (M)	SELCUM		2013
Otariid	235 dB re. 1 µPa (peak)	SPL	Impulsive	after NMFS
Pinnipeds (in water)	215 dB re. 1 µPa^2 s (M)	SELCUM		2013
LF, MF	230 dB re. 1 µPa (peak)	SPL	Non impulsive	after NMFS
Cetaceans	198 dB re. 1 µPa^2 s (M)	SELCUM		2013
HF	201 dB re. 1 µPa (peak)	SPL	Non impulsive	after NMFS
Cetaceans	180 dB re. 1 µPa^2 s (M)	SELCUM		2013
Phocid	235 dB re. 1 µPa (peak)	SPL	Non impulsive	after NMFS
Pinnipeds (in water)	197 dB re. 1 µPa^2 s (M)	SELCUM		2013
Otariid	235 dB re. 1 µPa (peak)	SPL	Non impulsive	after NMFS
Pinnipeds (in water)	220 dB re. 1 µPa^2 s (M)	SELCUM		2013

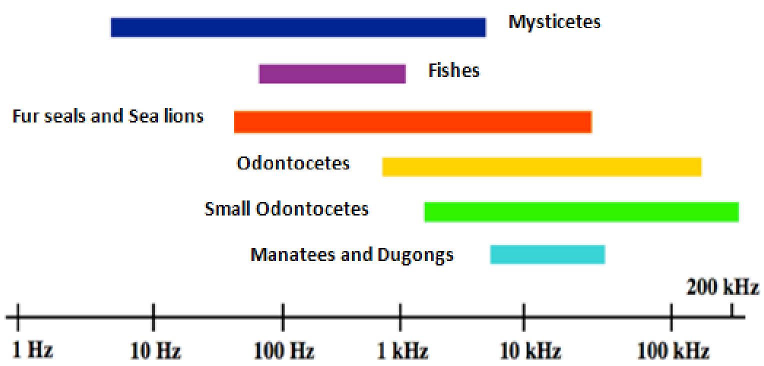
Known and potential effect on marine mammals

Construction noise *(piling noise)*

- **Detection/*audibility zone:*** **≈ 40-80 km**

- **Masking *zone:***

Literature studies argue that due to short signal duration and due to low duty cycle of the pile driving noise, significant masking problems should not occur.



Harbour seals:

≈ 80 km

MF Cetaceans:

up to 40 km

LF Cetaceans:

up to 80 km

Known and potential effect on marine mammals

Construction noise *(piling noise)*

- **Responsiveness *zone:***

✓ *Harbour porpoise:*

mild reactions ≈ **7- 25 km**

strong reactions ≈ **5 km**

This estimated responsiveness zone for harbor porpoise is confirmed by experimental studies conducted at different wind farm locations (i.e. Nysted, Horns Reef, Horns Rev, Horn Rev2). Aerial surveys at the Alpha Ventus wind farm (Germany), show the avoidance behavior by porpoises for a 40 km diameter area, around the construction site.

✓ *MF cetaceans:*

mild reactions ≈ **up to 10 km**

strong reactions ≈ **1 - 2 km**

Empirical studies on this topic are lacking

✓ *LF cetaceans:*

mild reactions ≈ **20- 50 km**

Responsiveness to impulsive sounds occurs in mysticetes, sometimes at considerable distances, and the potential of pile-driving noise to alter the behavior of the species can't be ruled out.

Known and potential effect on marine mammals

Construction noise *(piling noise)*

- **Hearing loss/injury *zone:***

There is no documented case of hearing injury caused by pile driving noise for marine mammals.
In the immediate vicinity of piling activities severe injuries cannot be excluded.
Mortality of marine mammals is very unlikely to occur during the construction phase of a wind farm except in very close proximity to the pile.

Severe injury/ mortality ≈ **10 m**

PTS (single event) ≈ **150 - 300 m (**harbour porpoise ≈ **500 – 1000 m)**

PTS (whole piling period) ≈ **3 – 5 Km (**harbour porpoise**)**

≈ **1 Km (**LF cetaceans**)**

assuming animal fleeing from the noise source at a rate of 1.5 ms^{-1}

Known and potential effect on marine mammals

Operational noise

Different literature studies all demonstrated that operational noise represents a light SPL increase of few dB re 1 μ Pa over the background levels.

- **Detection/*audibility zone:*** **< 20 km**
- **Responsiveness *zone:*** mild reactions ≈ **200 – 300 m** (harbour porpoise, bottlenose dolphin)
- **Hearing loss/injury *zone:***

Based on the available literature knowledge, and considering the available criteria it is unlikely that the sound levels during operation of wind turbines will be sufficient to cause physical injury or deafness to the marine mammals.

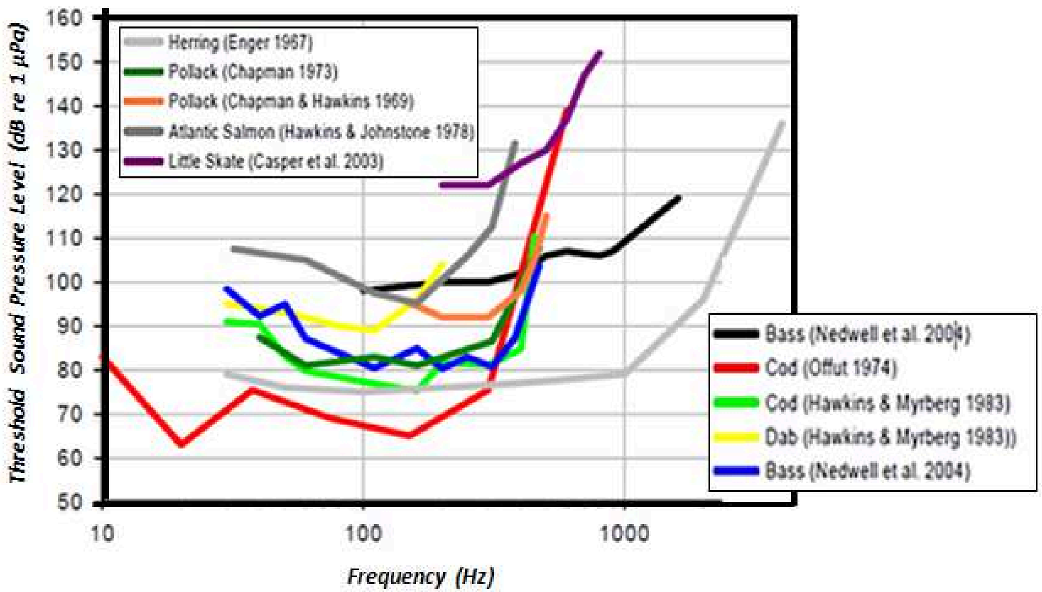
NB: measurements in literature are related to rather small turbines.
more and detailed measurements of whole wind farms in operation are needed to assess possible interference of sound waves coming from several turbines.

Hearing in fishes

Hearing thresholds/ Audiograms

Hearing capabilities among species vary greatly:
✓hearing specialists (fish species containing air-filled swim bladders). They can detect sounds to over 3 kHz with best sensitivity from about 300 to 1,000 Hz (Popper et al. 2003).

✓hearing generalists, the majority of fish species, can only detect sounds up to 500 - 1,000 Hz, with best hearing generally from 100 - 400 Hz (Popper et al. 2003).



Criteria and threshold levels for biological effects on fishes

Responsiveness / Behavioral respomse

Species	Exposure limit	unit	Source/ Type of Sound	behavioral response	Reference
all	75 dBht(species)	SPL		significant avoidance	Nedwell et al. 2007
	90 dBht(species)			strong avoidance	
ESA-listed	150 dB re. 1 µPa	RMS	Pile driving	temporary behavioral changes (startle and stress)	Normandeau Associates, Inc. 2012
all	168-173 dB re. 1 µPa	SPL peak	Pile driving	temporary behavioral changes (startle and stress)	McCauley et al. (2000)
all	200 dB re. 1 µPa	SPL peak	airgun	strong avoidance of the area- C-turn response	Pearson et al. (1992)

Hearing loss / Injury

Species	Exposure limit	unit	Source/ Type of Sound	Effect	Reference
all fish	220 dB re 1 µPa (peak tp peak))	SPL p-p		injury phisical trauma	Nedwell et al. 2007
	240 dB re 1 µPa (peak to peak)			lethal effect	
all fish	206 dB re. 1 µPa (peak)	RMS	piling noise Single strike	injury	FHWG. 2008
all fish	187 dB re. 1 µPa^2 s	SEL cumulative unweighted	piling noise	injury	FHWG. 2008
fish < 2 g	183 dB re. 1 µPa^2 s	SEL cumulative unweighted	piling noise	injury	FHWG. 2008

Known and potential effect on fishes

Construction noise *(piling noise)*

- **Detection/*audibility zone:***

The zone of audibility is linked to the individual species‘ hearing threshold and sensitivity.

Cod and Herring : **up to 80 km**

Salmon and Dab: **few km**

NB: audibility zone of piling noise for demersal species as dab, another important aspect to consider is the sound propagation through the sediment

- **Masking *zone:***

Pile-driving might affect communication indirectly due to stress induced by the noise. Pile driving noise can affect fish orientation and localization of prey negatively. The effect is probably greatest if it occurs during the fish’s spawning period, or if their foraging is prevented during growth periods of early life stages.
At the current base of knowledge cannot give enough information about the extension of the masking zone.

Known and potential effect on fishes

Construction noise *(piling noise)*

- **Responsiveness *zone:***

There have been very few experimental studies to determine the effects of wind farm noise on marine fish behavior to date and too little is known about the long-term effects of exposure to sound or about the effects of cumulative exposure to loud sounds.

Cod and Herring :

mild reactions ≈ **10 – 20 km**

strong reactions (C turn) ≈ **600 - 1000 m**

- **Hearing loss/injury *zone:***

Severe injury/ mortality ≈ **10 – 100 m**

PTS (single event) ≈ **up to 300 m**

PTS (whole piling period) ≈ **up to 14 Km** (assuming the fish do not flee)

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Known and potential effect on fishes

Operational noise

- **Detection/*audibility zone:***

Specialist: **up to 5 km**

Generalist **up to 1 km**

- **Masking *zone:***

For herring, which use mid frequency signal, masking from operational noise should occur at very close distances.

- **Responsiveness *zone:*** **up to 10 m**

Only few data are available to evaluate the responsiveness zone but it seems to be of negligible extension.

- **Hearing loss/injury *zone:***

Based on the available literature knowledge, it is unlikely that the sound levels during operation of wind turbines will cause physical damage to the fishes

Potential cumulative impacts

The potential impacts of sound need to be considered in a wider context, through addressing the consequences of acoustic disturbance on populations in conjunction with other stressors such as by catch mortality, overfishing leading to reduced prey availability and other forms of pollution such as persistent organic pollutants.

- ✓ Multiple sources of anthropogenic sound may interact cumulatively or synergistically. Anthropogenic noise sources, as commercial shipping, fishing and dredging vessels, produce lower noise levels compared to impact piling noise. There might be an increase of the risk of behavioral effect on some species of marine mammal and fish in case of temporally overlapping with the construction phase

- ✓ It is very important to evaluate the potential cumulative impacts especially in relation to the proximity (considering the impact zones of the piling noise) of other offshore projects which may utilize the impact piling technology like oil and gas platform as well as other wind farms. In this case there might be a significant increase of the risk of injury and behavioral reactions for marine fauna which need to be evaluate.

Best practise and mitigation procedures for underwater noise

In recent years several international organizations (OSPAR Convention - OSPAR, ACCOBAMS, ASCOBAMS, French Maritime Cluster, North Sea Foundation) have proposed guidelines on best environmental practices and on best available techniques to be implemented so as to mitigate the impact of noise on the marine environment.

Three common elements:

✓Best practices, a range of procedures that are applied according to defined protocols and decision trees.

✓Noise reduction technologies, either able to reduce the noise produced by conventional sources, or technical solutions having lower noise emissions than conventional techniques.

✓Software, conceived for biological risk assessment and for the real-time detection of the presence of marine mammals. Web platforms storing wide biological and ecological databases witch can be used as a complementary tool, useful to carry out a preliminary environmental assessment.

Best practise and mitigation procedures for underwater noise

Best practices *(some examples)***:**

Planning phase of the project

- ✓ consider the species that might be present. especially presence of marine mammals. Impact assessments carried out prior to the beginning of works;
- ✓ define biologically important zones as the Areas of Special Concern for Beaked whales or marine sanctuaries;
- ✓ use a noise propagation modelling outputs to estimate the extent of an Exclusion Zone (EZ) and in case of no modelling result available use a radius of 750 m for construction work as pile driving;

Best practise and mitigation procedures for underwater noise

Best practices *(some examples)*:

Operational phase of the project

- ✓ use of *Acoustic Mitigation Devices (AMD)*. The approach here is to use sound signals to warn the sensitive species, such as marine mammals so that they could move away from potential danger activities like piling activities.
- ✓ use the *Soft Start protocol*. This procedure should have a minimum duration of 20 minutes. Soft start procedure should be delayed if cetaceans enter the Exclusion Zone
- ✓ use of the *Visual Monitoring Protocol.* Dedicated and independent Marine Mammal Observers (MMO) should watch the Exclusion Zone for 30 min before the beginning the soft start procedure.

Best practise and mitigation procedures for underwater noise

Best practices *(some examples)***:**

Post activity monitoring and reporting

- ✓ draft a detail report, including the procedures that were implemented, the sightings, behavioral observations, etc;
- ✓ make the report publicly available in order to contribute to deepen available knowledge and improve mitigation frameworks;

Best practise and mitigation procedures for underwater noise

Noise reduction technologies *(some examples)*:

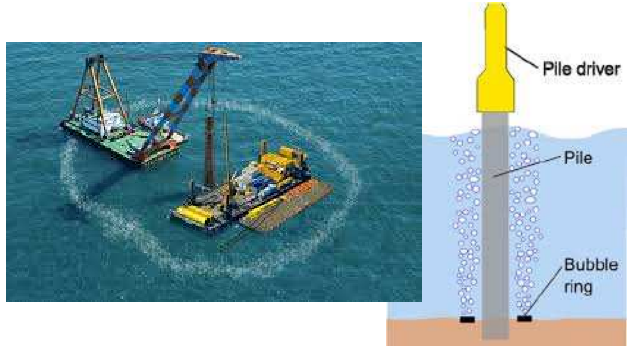
Reduction technologies of source level

- ✓ *Changing the parameter for pile stroke. I.e.* prolonging the pulse duration and so the contact time of the hammer, reduces the corresponding sound emission as a consequence of the reduced amplitude of the pile vibration. ***10 -13 dB reduction***

Best practise and mitigation procedures for underwater noise

Noise reduction technologies
(some examples):

Reduction solutions of noise trasmission



- ✓ *<u>Bubble curtain</u>* A bubble curtain is a sheet of air bubbles that are produced around the location where the piling activity occurs. The bubbles in the bubble curtain create an acoustic impedance mismatch between the water and air trapped in the bubble, which results in sound attenuation across the bubble curtain.

Big Air Bubble curtain Pipe with drilled holes placed around the whole foundation on the seabed
Noise reduction:
11-15 dB (SEL), 8-14 dB (peak) for a single bubble curtain;
17 dB (SEL), 21 dB (peak) for double bubble curtain

Little air bubble curtain *There are several variations of this solution with different noise reduction ability*.

<u>Successfully tested, represent a proven technology</u>

Best practise and mitigation procedures for underwater noise

Alternative technologies with lower noise emission (some examples)**:**

- ✓ *Vibro-drilling foundation*
- ✓ *Gravity-base Foundations*
- ✓ *Jacket Foundation*
- ✓ *Floating Foundations*

Best practise and mitigation procedures for underwater noise

Software (some examples)**:**

- ✓ acoustic mapping tools in combination with tools to characterize the distribution and density of marine species can provide important information for risk assessment

- ✓ acoustic propagation and modelling tools, available for assessing the underwater noise impacts in coastal waters and for planning the mitigation procedures; these tools, which are implemented in commercial software, could be used during the environmental impact assessments

- ✓ real-time monitoring software mainly used during passive acoustic monitoring (PAM). By using these tools, PAM operators become the most important resource during night-time and bad weather conditions.