

# Offshore wind farms – ecological effects of noise and habitat alteration on fish

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*To my mother, Bittan Andersson (1949-2007),  
for all support and encouragement*

*I miss you*



## ABSTRACT

There are large gaps in our understanding how fish populations are affected by the anthropogenic noise and the alteration of habitat caused by the construction and operation of offshore wind farms. These issues are of great importance as the construction of offshore wind farms will increase all over the world in the near future. This thesis studies these effects with a focus on fish. The wind turbine foundations function as artificial reefs and are colonized by invertebrates, algae and fish. The epibenthic assemblages are influenced by factors such as hydrographical parameters, time of submergence, distance to natural hard bottom, material and texture (PAPER I, II). Once an epibenthic assemblage has been developed, fish utilize it for different ecosystem services such as food, shelter, and spawning and nursery area. Benthic and semi-pelagic species show a stronger response to the introduced foundation than pelagic species, as it is the bottom habitat that has mainly been altered (PAPER I, II). Pelagic species could be positively affected by the increased food availability - but it takes time and the effect is local.

Construction noise like pile driving creates high levels of sound pressure and acoustic particle motion in the water and seabed. This noise induces behavioural reactions in cod (*Gadus morhua*) and sole (*Solea solea*). These reactions could occur up to tens of kilometres distance from the source (PAPER III). During power production, the wind turbines generate a broadband noise with a few dominating tones (PAPER IV, V), which are detectable by sound pressure sensitive fish at a distance of several kilometres even though intense shipping occurs in the area. Motion sensitive species will only detect the turbine noise at around a ten meter distance. Sound levels are only high enough to possibly cause a behavioural reaction within meters from a turbine (PAPER IV, V).

**Keywords:** *renewable energy, fish population, artificial reef, attraction vs. production, habitat structure, reef effect, FAD, bioacoustics, noise disturbance, fish behaviour, detection range, threshold, masking, fish communication and hearing.*



## SVENSK SAMMANFATTNING

Inom de närmaste tjugo åren kommer tiotusentals nya vindkraftverk byggas i europeiska vatten för att öka den förnyelsebara energiproduktionen och minska utsläppen av koldioxid. Men det finns flera frågetecken om hur det marina livet påverkas av havsbaserad vindkraft då ny hårbotten tillförs till området och ett nytt ekosystem bildas lokalt, men även på grund av att betydande ljudnivåer skapas under framför allt byggnationen men även under produktionsfasen. Denna avhandling behandlar effekterna av denna påverkan med fokus på fiskekosystemet.

Vindkraftverksfundament kan skilja sig åt i både storlek, material (stål eller betong) och konstruktion, men gemensamt är att de tillför ny hårbotten till både den fria vattenmassan och botten. Många fiskar och ryggradslösa djur har frisimmande larver och dessa kommer att fångas upp av fundamenten och ett nytt ekosystem bildas på ytan och nedanför. Fastsittande filtrerande organismer som t.ex. musslor, havstulpaner, hydroider, sjöpungrar och maskar etablerar sig relativt snabbt på de lediga ytorna. Fundamenten fungerar då som så kallade konstgjorda rev, även om de har ett annat huvudsyfte. Vilka arter som koloniserar de vertikala ytorna beror på vilken tid på året som de byggs eftersom olika organismer förökar sig under olika månader, vilken typ av botten som fundamenten byggs på och på materialets ytstruktur. Organismer som havstulpaner och rörbyggande havsborstmaskar fäster sig lättare på släta stålytor, medan hydroider och sjöpungrar föredrar mera skrovliga betongytor (PAPPER I). Alger kommer också att kolonisera fundamenten men det tar lite längre tid då de växer långsammare (Papper I, II). Ekosystemet kommer att utvecklas över tiden och det först etablerade organismerna påverka vilka ytterligare djur och växter som kommer att kolonisera fundamenten. Artsammansättningen på fundamenten kommer att skilja sig från de naturliga hårbottarna och nya arter för området kan etablera sig, framförallt om fundamenten placeras på en mjukbotten (PAPPER I, II). Bland fiskar kommer bottenlevande arter att påverkas mest av att det byggs fundament i området eftersom det framförallt är deras livsmiljö som ändras (PAPPER I, II). Fiskar som föredrar hårbotten kommer lokalt att öka i antal och det kan antingen bero på att de attraheras till det nybildade ekosystemen, men också på att nya individer tillkommer då fundamenten fungerar som lek- och uppväxtplats (PAPPER I, II). Fiskar som lever i det öppna vattnet kan lockas till det nybildade ekosystemet på och omkring fundamenten, eftersom det kan förse dem med mat och skydd. Påverkan är dock lokal och det tar tid att upptäcka någon effekt på det totala antalet fiskar i ett större område. Detta beror på att det finns en ganska stor naturlig variation i fiskdensitet och att det tar flera år för många fiskarter att bli könsmogna och få möjlighet att reproducera sig.

Det är främst under byggnationen av en park, vid pålningen av fundamenten, som riktigt höga ljudnivåer (både ljudtryck och partikelrörelse) kan uppstå, nivåer som har visat sig både döda och skada fisk men även störa viktiga biologiska funktioner som lek. De flesta fiskar hör bra och eftersom ljudet färdas väldigt snabbt och långt under vattnet blir det en storskalig påverkan. Fiskar som kan registrera ljudtryck, som t.ex. torsk, kommer att reagera på konstruktionsljud på flertalet kilometer ifrån en sådan aktivitet (PAPPER III). Fiskar som bara hör partikelrörelse, som t.ex. plattfiskan tunga, kommer även att reagera på konstruktionsljud men eftersom det inte finns några mätningar av partikelrörelser vid pålning kan inga avstånd beräknas men avståndet är sannolikt kortare än för de övriga fiskarna (PAPPER III). Eftersom det finns skillnader mellan och inom arter vid vilka ljudnivåer de reagerar på ett ljud, kan man inte sätta ett enskilt tröskelvärde utan ett intervall är mera rimligt. Vindkraftverken bullrar inte bara under konstruktion utan även under drift. En ljudspridningsmodell baserad på mätningar i en vindkraftpark visar att ljudnivåerna inte är så höga att de är direkt skadliga men att de är hörbara på flera kilometers håll för de fiskar som registrerar ljudtryck, även om andra ljudkällor som fartyg finns i området (PAPPER V). Detta beror på att vindkraftverken producerar toner som skär igenom den befintliga ljudbilden. Inom ett par meter från fundamenten är ljudnivåerna så höga att det finns risk för att fiskarnas egen kommunikation överröstas eller att beteendet kan påverkas (PAPPER IV, V). Detta gäller även fiskar som bara registrerar partikelrörelse (PAPPER IV). Även om fiskarna kan vänja sig vid ljudet kan det finnas andra negativa konsekvenser av att leva i en bullrig miljö, som exempelvis stress, vilket vi idag vet väldigt lite om och detta tillsammans med vilken påverkan andra ljudkällor, som t.ex. båtar, har på fisk, måste studeras i framtiden.

## LIST OF PAPERS

This thesis is based on the following papers, which are referred to in the text by their roman numerals:

- I. Andersson, M. H., Berggren, B., Wilhelmsson, D., and Öhman, M. C. (2009). "Epibenthic colonization of concrete and steel pilings in a cold-temperate embayment: a field experiment" *Helgoland Marine Research*, **63**, 249–260.
- II. Andersson, M. H., and Öhman, M. C. (2010). Fish and sessile assemblages associated with wind-turbine constructions in the Baltic Sea. *Marine and Freshwater Research*, **61**, 642–650.
- III. Mueller-Blenkle, C., McGregor, P. K., Gill, A. B., Andersson, M. H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D., and Thomsen, F. Pile-driving sound affects the behaviour of marine fish. Manuscript.
- IV. Sigray, P., and Andersson, M. H. "Particle motion measured at an operational wind turbine in relation to hearing sensitivity in fish. Manuscript conditionally accepted for publication in the *Journal of the Acoustical Society of America*.
- V. Andersson, M. H., Sigray, P., and Person, L. K. G. Wind farm noise influence on the audibility of fish. Manuscript.

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### **My contribution to the papers:**

Main applicant (I, IV, V), planning the study and experimental design (I, II, IV, V), performing experiment or fieldwork (I-V), data analysis (performing I, II, V and participating III, IV) and writing the paper (main writer I, II, V and participating III, IV).

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## 1 INTRODUCTION

Almost all fish populations and their habitats over the world are affected by more than natural causes such as El Niño, since predation by humans in terms of intense fishing has been increasing for decades (Jackson *et al.*, 2001; Watson and Pauly, 2001; Hilborn *et al.*, 2003; Thursan *et al.*, 2010). In the last 100 years mankind has become the number one predator on most fish populations, limiting the amount of spawning biomass. Fishes are also affected by the increased anthropogenic nutrient enrichment (eutrophication) in the oceans altering food-web structures and resource availability as well as spawning and nursery habitats (Baden *et al.*, 1990; Vitousek *et al.*, 1997; Micheli, 1999). In addition, marine litter in the form of small plastic particles can be ingested by fish resulting in reduce food uptake, cause internal injury and death (Derraik, 2002; Gregory, 2009). Other activities such as exploration and extraction of oil and gas deposits, commercial shipping, offshore wind farms, military operations and boat tourism are all claiming rights to use the oceans for their purposes. These activities add noise to the ambient sound in the oceans affecting marine life (Ainslie *et al.*, 2009; Hildebrand, 2009; Kikuchi, 2010). In addition, ocean constructions destroy natural seabed and add new substrate in areas that often are lacking hard surfaces, and consequently introducing new species (Wilhelmsson *et al.*, 2006a; Brodin and Andersson, 2009; Wilson and Elliot, 2009). Thus, it is vital to understand the solitary as well as cumulative effect of these activities on the marine ecosystem, if we are to achieve a sustainable marine environment, enjoyable for future generations.

The use of renewable energy sources has increased and will increase over the next decades in the ambition to decrease carbon dioxide emissions and stop global warming (Krupp and Horn, 2008). However, the construction of renewable energy sources offshore alter local marine ecosystems (Boehlert and Gill, 2010; Wilhelmsson *et al.*, 2010). Out of wind, wave and tidal power, wind power is the only energy source commercially available today at a large scale. In Europe, the European Wind Energy Associations (EWEA) has set a goal of having 230 GW installed wind power capacity, including 40 GW offshore, by 2020 that is equivalent to 14-17% of EU's total electricity demand. By 2030 their estimation is 400 GW installed out of which 150 GW from offshore (EWEA, 2010). This is an ambitious goal given that 74 GW was installed in 2009 out of which only 2 GW comes from offshore wind power (EWEA, 2010). To reach their goal in 2020, 10 000 new offshore wind turbines (4 MW each) need to be built in coastal and offshore areas and another 22 000 (5 MW each) by 2030 occupying several hundred square kilometres of the coastal environment.

There are several benefits of placing wind power turbines offshore compared to onshore, such as usually higher wind potential (Bergström and Söderberg, 2008), less competition for space and minimal aesthetic influence (Taylor, 2004). Today most wind farms are built or applications are pending for building in shallow water areas (at 5 to 30 m depth) several kilometres from the coast, on offshore banks. These banks are often of high biological importance as feeding and spawning grounds for fish and supplying coastal areas with eggs and larvae of various marine organisms (Naturvårdsverket, 2006). Concerns over the potential impact from offshore wind power installations on biodiversity have been raised, including habitat loss, changed hydrological conditions, noise disturbance and increased emissions of electromagnetic fields (Gill, 2005; Zettler and Pollehne, 2006; Broström, 2008; Slabbekoorn *et al.*, 2010).

Notably, by adding artificial structures, i.e. offshore wind farms, to the seabed the ecosystem is locally altered and a new epibenthic assemblage is developed which could enhance fish densities. Whether this is a positive or negative effect can, however, be debated. When dealing with the impact on the marine environment it is important to consider the whole life cycle of the offshore wind farms (Gill, 2005). The main impact to the ecosystem occurs during the relatively short period of construction and then again during the described removal phase (no large wind farms have been removed yet). Noise from pile driving and boat activities as well as increased turbidity and destruction of habitat are a few of the described impacts (Wilhelmsson *et al.*, 2010). During the operational phase (about 20 years), noise and electromagnetic fields as well as impact on the fish ecosystem are of most concern (Ehrich

*et al.*, 2006; Öhman *et al.*, 2007; Popper and Hastings, 2009; Slabbekoorn *et al.*, 2010). The uncertainty of the effect is mainly related to the large knowledge gaps, especially regarding activities generating noise associated with the construction and the operational phase. This status was acknowledged by HELCOM (Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area) and the EU Marine Strategy framework, who are working on defining and implementing indicators describing good environmental status of the Baltic Sea and other European seas - so far the limited knowledge in these areas make this work difficult (Tasker *et al.*, 2010).

Most studies from monitoring programs and surveys of the fish ecosystem around offshore wind farms are only published as grey reports to the contractors and rarely in any other form (but see Westerberg, 1994; Dong Energy *et al.*, 2006; Wilhelmsson *et al.*, 2006a). Nonetheless, results indicate that the foundations might function as artificial reefs with increasing food availability and shelter for some fish species. However, the timescale complicates the matter because there is a natural variation of the fish ecosystem over several years (Holbrook *et al.*, 1994; MacKenzie and Köster, 2004; Ehrich *et al.*, 2006).

### **1.1 The aim of this thesis**

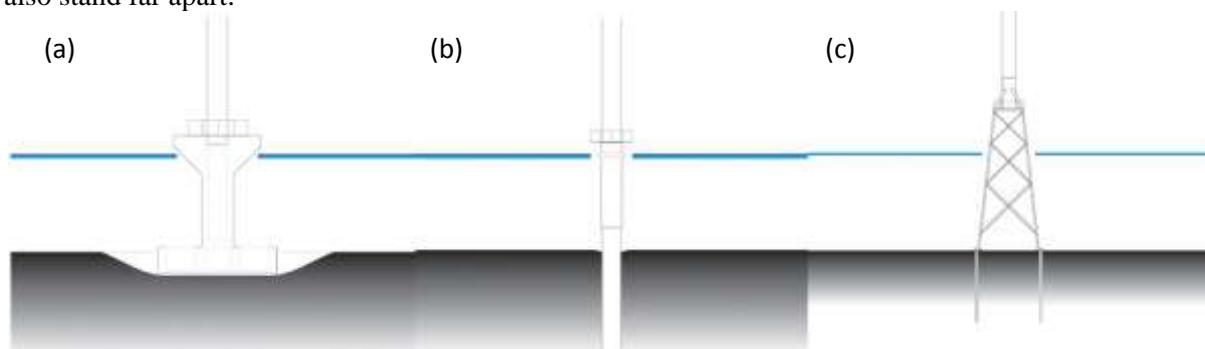
The aim of this thesis was to study how offshore wind power influence fish focusing on habitat and noise effects. The noise generated during the construction of wind farms, i.e. pile driving noise is tested for disturbance effects in terms of behavioural reactions in fish. Noise during the production phase is measured and zones of impact estimated and discussed. Additionally, the early recruitment of sessile organism and fish on the introduced foundations are studied. A specific aim was to incorporate experimental observations from the field in this work. Field trials were done in Sweden and Scotland.



Sunset over the wind farm Lillgrund, located in the Öresund strait between Sweden and Denmark. © Mathias H. Andersson.

## 2 ARTIFICIAL REEFS

Man-made constructions like wind farms in the coastal areas and open oceans can be viewed as artificial reefs, i.e. adding vertical hard substrate in an environment otherwise dominated by soft bottom and empty water even if this was not their original purpose (Svane and Petersen, 2001; Wilhelmsson *et al.*, 2006a; Wilson and Elliott, 2009). Three main techniques are used today to attach wind turbine foundations to the seabed; gravitation, monopile and jacket foundations (Nikolaos, 2004; Hammar *et al.*, 2010) (Fig. 1). Floating turbines exist as well, but only in demonstration projects, e.g. Hywind in Norway. The foundations all have different impacts on the ecosystem as they are constructed using different techniques and are of different size and material. However, these structures should not be regarded as surrogates for natural substrates since epibenthic assemblages on artificial surfaces were shown to differ compared to assemblages on natural hard substrates (Connell, 2001; Perkol-Finkel and Benayahu, 2007; Wilhelmsson and Malm, 2008). Further, there is a fundamental difference between commonly used artificial reefs, which have been thoroughly studied (reviewed in Baine, 2001), compared to large scale constructions such as oil-rigs, wind farms and bridge pillars since the latter penetrate the whole water column, adding hard substrate in an otherwise empty sea and also stand far apart.



**Figure 1.** Illustrations of the three most common foundations used for offshore wind farms. (a) Concrete gravitation foundation, (b) steel monopile foundation and (c) steel jacket foundation. Illustrations modified from Hammar *et al.* (2010) with curtsy of Linus Hammar.

### 2.1 Epibenthic assemblage

Factors influencing the epibenthic invertebrate and algae assemblages on and around the artificial reef are salinity and temperature (Thorman, 1986), water movement (Guichard *et al.*, 2001), light availability (Glasby, 1999), depth (Relini, 1994), inclination of the surface and material and texture (Glasby, 2000; Somsueb *et al.*, 2001; Knott *et al.*, 2004; Becerra-Muñoz *et al.*, 2007). The initial development of macromolecule film and bacteria colonization created shortly after submergence either favours or deter larva from settling, which determines the on-following colonization (Wahl, 1989). In addition, time of submergence is of great importance in the beginning of the colonisation phase as different marine organism release their eggs and larvae during different times; these will compete for the available space on the artificial surface (Anderson and Underwood, 1994; Perkol-Finkel *et al.*, 2005).

As wind turbine foundations usually are located far away from the coast in areas previously lacking hard substrate in the water column and surface, they might function as refuges and stepping-stones for non-native species. Numerous species are transported all over the world on ships hulls and in ballast water tanks. These species could find new suitable habitats on these structures (Leppäkoski and Olenin, 2002). This has actually already happened when two new species were recorded at the wind farm Horns Rev in Denmark that previously had not been observed in Danish waters: the amphipods *Jassa marmorata* and *Caprella mutica* and the midge *Telmatogon japonicus* (Dong Energy *et al.*, 2006). The amphipods were found in high numbers on the foundation and were overall the most abundant species recorded. The same midge was also recorded at the wind farms Utgrunden and Yttre Stengrund in Sweden in the southern Baltic Sea in 2007 (Brodin and Andersson, 2009). The hypothesis is that these were transported to the area via ships.

## 2.2 Fish assemblage

Fish responds to several habitat characteristics like complexity, availability of food, shelter and hydrographical parameters such as water temperature and salinity (Connell and Jones, 1991; Magill and Sayer, 2002). The balance of these parameters is essential for the survival and reproduction of most fish species. Other important habitat properties include water depth, the substrate character and oxygen concentrations (Kramer, 1987; Phil and Wennhage, 2002). Substrate and sufficient oxygen concentrations are particularly important for the near-bottom fish species, as they are less mobile. In temperate regions water parameters change over the seasons and sometimes even between days. It is vital to understand the impact from these factors when predicting the effect of wind farms on fish ecosystems as they determine if a certain species of fish will be in the area or not. When estimating fish abundance several methods can be used, e.g. eco sounders (bottom or hull mounted), trawls, fyke and gill nets as well as visual estimations by divers (see Fig. 2). As they all work in different ways focusing on certain target species, different parts of the fish ecosystem will be sampled. Thus, care has to be taken when choosing sample method for estimation of fish abundance around offshore wind farms since different results might be obtained as a result of the chosen method (Andersson *et al.*, 2007a).

To understand fish population dynamics, the underlying processes have to be understood. Such processes are rates of birth (i.e. recruitment), immigration, emigration and death. For many fish species these factors form a complex web of demographic rates. Larval and juvenile stages mainly contain both a pelagic and a benthic phase, thus making it difficult to study the natural development of individual fish and populations (Caley *et al.*, 1996; Cushing, 1996). The dispersal of recruits plays an important role in establishing the origin of a population. The population can be described as “open” if it receives its new recruits from neighbouring or even distant populations, or as “closed” when the population primarily receives its new recruits from its own residents (Mora and Sale, 2002).

Several studies have reported high abundances of fish around and in the vicinity of artificial reefs (reviewed in Brickhill *et al.*, 2005). Two hypotheses have been proposed for the high densities: attraction and production (Bohnsack, 1989). The former suggests that fish is gathered around the artificial reef merely as a consequence of fish behaviour that is, fishes are more attracted to a structure compared to a barer featureless bottom. However, the fish density in the area as a whole will not increase, due to limitations in larval and food supply. The latter hypothesis states that the increase of fish is due to new production, possible when new substrate is added since it provides new habitat for settling, foraging and protection from predators (Bohnsack, 1989).



**Figure 2.** Different methods to sample fish around offshore wind farms. (a) A gillnet and (b) visual census used around Utgrunden wind farm in the Kalmar strait and in Gåsevik (PAPER I, II), (c) a fyke net used by the Swedish Department of Fisheries during the monitoring program of the wind farm Lillgrund in the Öresund strait. © Mathias H. Andersson

Studies from several different marine environments have had the ambition to evaluate the effectiveness of artificial reefs in fish habitat restorations (reviewed in Seaman 2007), without reaching consensus on the effectiveness in terms of new production of biomass (Powers *et al.*, 2003; Brickhill *et al.*, 2005). The overall conclusion is that the effect is dependent on the species and life stage of the fish. As it takes time for the new epibenthic invertebrate and fish assemblage to develop on an introduced structure such as offshore wind foundations, several years of monitoring is required to grasp the environmental impact. Species will come and go based on the level of disturbance occurring. More research is needed on the impact from offshore constructions to the ecosystem, which includes both continuously large-scale field monitoring of existing wind farms and experiments testing disturbance hypothesis and individual behaviour reactions.

### 3 UNDERWATER ACOUSTICS

Sound energy propagates through the water in terms of motion (displacement) of the fluids particles that induce longitudinal pressure changes. The rate of these pressure changes ( $f$ ) is measured in cycles per second (Hz) and the speed (m/s) is related to the properties of the medium. In fresh water, sound travels ( $c$ ) at about 1497 m/s at 25 °C and in sea-water (34 PSU) at a slightly higher speed of 1560 m/s due to the higher density. The wavelength ( $\lambda$ ) of the sound is the spatial period of the wave i.e. the distance (in meter) over which the wave's shape repeats. The relationship between these factors is described by the equation

$$c = f\lambda.$$

As a result, high frequencies have short wavelengths and low frequencies have longer wavelengths. This is important to keep in mind when comparing studies performed in areas with different depth and water properties. Sound pressure level (SPL) is the difference in pressure between the average local pressure and the pressure in the sound wave. The pressure is measured in Pascal, but as there could be large differences in pressure the logarithmic scale of decibel (dB) was adopted to describe sound pressure. To convert pressure into decibel the following equation is used

$$SPL = 20 \log(P/P_{ref}),$$

where  $P$  denotes the measured pressure and  $P_{ref}$  the reference pressure for the medium, in water 1  $\mu$ Pa. The displacement component ( $v$ ) of the particle motion and sound pressure ( $P$ ) can be calculated if the impedance ( $Z$ ) of the medium is known, by using the following equation

$$v = Z/P.$$

However, even though the impedance can be calculated from the density of the medium it would only be applicable under certain conditions, e.g. in an acoustic free field with no reflecting boundaries and an unchanging sound speed in the water column; this is not a commonly found situation in the sea, except in deep oceans. Therefore, to be able to describe the sound field in the water both sound pressure and particle motion needs to be measured. The particle motion component of sound can be described by either displacement (m), particle velocity (m/s) or particle acceleration ( $m/s^2$ ) as they are time derivatives of each other and therefore mathematically related. Close to a sound source (“near field”) and in shallow water, there is no analytical relation between pressure and motion due to the complexity in the acoustic field affected by the impedance and interference. Further away (“far field”) and in a free acoustic field the ratio between particle motion and sound pressure is constant and one can thus be derived from the other if the impedance is known. Sound pressure is measured by a hydrophone containing a piezoelectric material, converting pressure into volts. Particle motion is more difficult to measure, but can be calculated as described above or be numerically determined by the pressure gradients between two hydrophones. An alternative at hands is to employ accelerometers, which measures particle acceleration. An advantage with this choice is that the measurement gives information on the particle motion in three dimensions. Few commercial sensors are unfortunately available for field measurements.

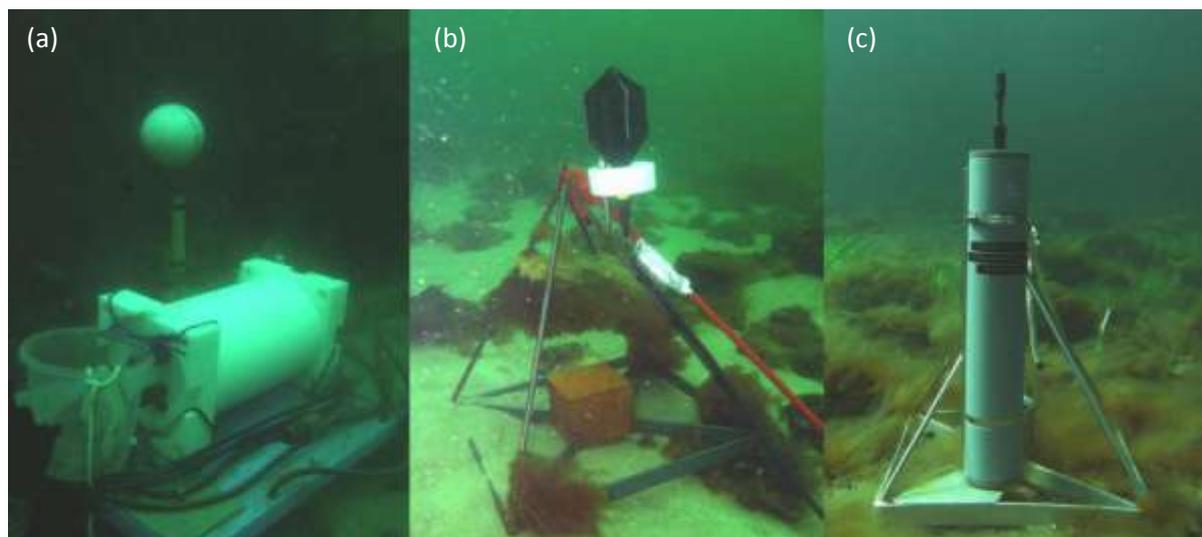
A sound wave will lose energy as it expands from the sound source. Several factors influence the transmission loss (TL) of the sound energy. A complication is that transmission loss is frequency dependent. In a free acoustic field without any reflecting boundaries, the sound will decrease with  $20 \cdot \log$  (distance) (“spherical spreading”) as the energy is dispersed over a large area. In shallow water the bottom and water surface will reflect the sound, causing interference, the decrease is less:  $10 \cdot \log$  (distance) (“cylindrical spreading”). Another factor influencing the propagation in water is absorption, which increases with increasing frequencies and with increasing salinity. The effect of absorption is small on frequencies below 1 kHz. An approximate estimate shows that it reduces the sound level with less than 0.1 dB per kilometre in a saline environment. Source level (SL) is used to describe the sound

intensity at 1 m from the sound source. The source level is either estimated or measured. The received sound level (RL) at a distance ( $r$ ) from a source can be calculated from the source level when the transmission loss is known by

$$RL(r) = SL(1m) - TL(r).$$

During construction and operation of offshore wind farms, noise is radiated into the water. The character and sound levels of operational noise will be described in detailed in section 5.2.2, but below follows a short description of piling noise. Impact pile driving is the most common way to anchor a wind turbine foundation into the seabed. It can be large 3 to 6 m wide and 20 to 30 m long monopile foundations or smaller piles (less than 1 m wide) used when a jacket foundation is secured to the seabed. A hydraulic or diesel fuelled hammer hits the pile repeatedly to drive it into the seabed. The single acoustic pulse created during impact is between 50 and 100 ms in duration with app. 30 - 60 beats per minute. It usually takes several hours to drive one pile into the bottom. This activity creates high levels of sound pressure and acoustic particle motion that are transferred through the pile into the water and seabed. Noise is radiated from the pile itself, but it could also radiate back from the seabed into the water column. The sound from pile driving is transient and discontinuous, to be compared with the more broadband and continuous sound from an operational wind farm. Several acoustic measurements of sound pressure during piling have been performed, showing source levels of over 180 dB re  $1\mu\text{Pa}_{(\text{peak})}$  at 1 m (Madsen *et al.*, 2006; Betke *et al.*, 2004; Betke, 2008; Erbe, 2009). However, there are no published studies on levels of particle motion during a pile driving operation. Most of the piling pulse energy is below 1 kHz, overlapping with frequencies where fish both receive and produce sound. There is a continuous discussion among scientist in what unit pile driving noise and similar transients (e.g. air-gun noise) should be expressed. The two most common ways are sound pressure level (SPL) (expressed in dB re  $1\mu\text{Pa}_{\text{peak}}$ ) showing the maximum pressure within the pulse and cumulative sound expose level (SEL) (expressed in dB re  $1\mu\text{Pa}^2\cdot\text{s}$ ) which sums up the energy of all pulses over a certain time window (Southall *et al.*, 2007).

Today, there is no long-term monitoring of ambient sound available to science in any European country. Measuring sound in the oceans at different locations and during different times of the year, both natural and anthropogenic, is important if we are to understand our impact on the ocean. (See Fig. 3 for different systems used to measure underwater noise). The term “soundscape” has been adapted to describe the sound in the terrestrial environment and this applies as well to the underwater environment as it is full of sound that is used in biological interactions and for marine organisms to orient themselves in the water. This will be described further in the next chapter.



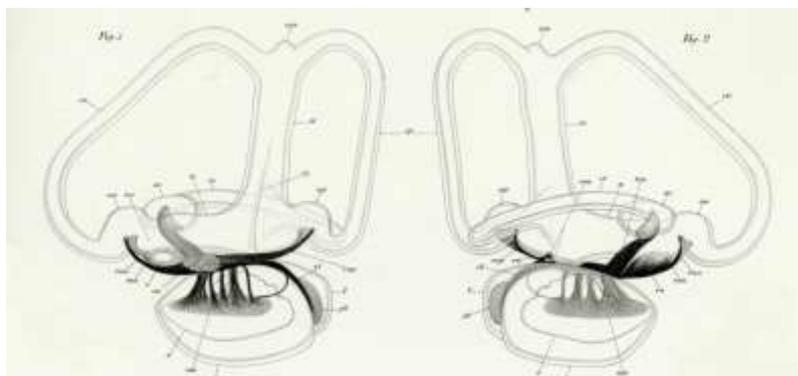
**Figure 3.** Acoustic sensors used in the studies. (a) Particle motion sensor developed and used in **PAPER IV**, (b) Brüel & Kjær 8101 hydrophone and (c) DSG-ocean hydrophone used in **PAPER V**. © Mathias H. Andersson.

## 4 FISH BIOACOUSTICS

### 4.1 Sound and hearing

There are a lot of biological sounds in the sea. Fish uses sound in various behavioural interactions such as finding prey, scare away competitors or to be aware of an approaching predator. Many species produces sound using muscles around their swim bladder or by stridulating teeth or fin rays to attract a mate or during spawning (Bass and Ladich, 2008; Kasuman, 2008). Additionally, sound also gives information about abiotic conditions like currents and winds as well as the location of coastlines and reefs and are used for orientation by fishes (Lagardère *et al.*, 1994; Tolimieri *et al.*, 2000). This auditory scene extends much further than the visual scene that could be limited by low visibility, and provides fish with an overall very broad view of their world. One of the earliest records of an observation of sound produced by fish was given by Aristotle's (350 B.C.E) in *Historia Animalium* where he stated "*Fishes can produce no voice, for they have no lungs, nor windpipe and pharynx; but they emit certain inarticulate sounds and squeaks*". How fish detects sound was not really shown until the beginning of the 20th century when G.H. Parker (1903) was one of the first to demonstrate that fish can detect sound. However, it was not until the mid 1960 and early 1970 that the field of fish bioacoustics started. Today it is an interdisciplinary field that combines biology, psychology, physics and mathematics. Even though research on fish hearing has been performed for more than 50 years, there are still large knowledge gaps in our understanding of hearing mechanism and sound production and its relevance to behaviour (Popper and Fay, 2010). There are up-to-date 31 900 species of fish and an unknown number of species not yet known to science (Froese and Pauly, 2010). Out of the ones we do know about, only a small fraction has been studied in terms of their abilities to detect sound pressure and motion. However, it is clear that all teleost fish have inner ears, equipped to detect motion, and some species having a swim bladder can detect sound pressure. Additionally, specialization to increase sound pressure sensitivity even further seems to have evolved simultaneously, in different fish families (Ladich and Popper, 2004).

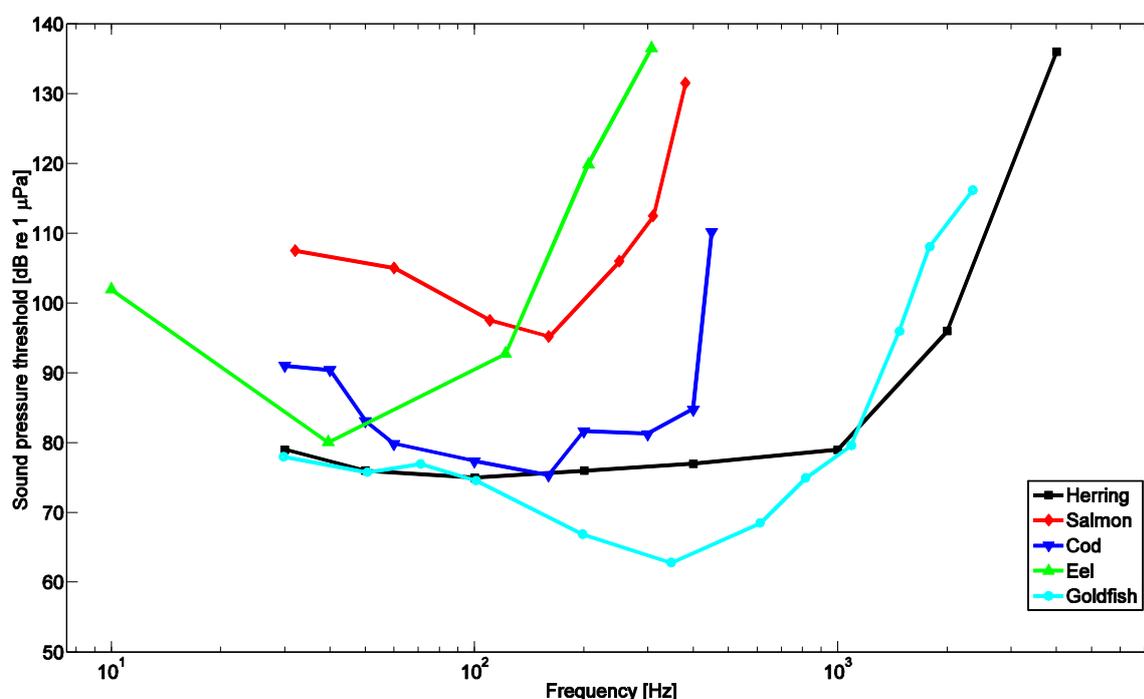
As mentioned earlier, all teleost fish has two inner ears that consist of three semicircular canals, each oriented perpendicularly to each other with a sensory region at the base (Popper *et al.*, 2003) (Fig. 4). The sensory region contains three otolith organs (the sacculus, lagena, and utriculus), each containing a calcareous otolith mechanically connected to a sensory epithelium (maculae) by a thin membrane. Sensory hair cells are embedded in the epithelium and register the relative movement between the otolith and the epithelium. This movement is caused by the difference in density of the otolith and the epithelium resulting in a shear movement at different amplitudes and phases. This mechanical stimulation of the hair cells induces a signal that stimulates the nervous system. The otolith organs have two functions; determining the head's position (relative to gravity) and sound detection. It is the particle motion component of the sound that stimulates the otoliths, making them behave as simple harmonic oscillators (de Vries, 1950). Studies have shown that out of particle displacement, velocity and acceleration, the last is the component used in sound detection by the otoliths (Hawkins, 1993; Fay and Edds-Walton, 1997; Sand and Karlsen, 2000).



**Figure 4.** Illustration of the inner ears of salmon (*Salmo salar*) made by Gustaf Retzius (1881). The three semicircular canals are seen oriented perpendicularly to each other with otoliths at the base. This scanned copy of the original illustration was kindly supplied by Arthur N. Popper.

For detection of sound pressure, the fish must have a swim bladder or other gas-filled chamber, (usually found in the abdominal cavity), which can convert the pressure into motion and be detected by the otolith. There is a considerable variation in size, shape and location of the swim bladder between species as well as different specialisations to enhance the transfer of pressure into motion. The most studied enhancement is the Weberian ossicles, which are small bones connecting the swim bladder to the saccule otolith found in fish's belonging to the superorder Ostariophysi, e.g. carp (*Cyprinus carpio*), goldfish (*Carassius auratus*) and roach (*Rutilus rutilus*). This specialisation has led to sensitivity from a few Hz up to several kHz with a sound pressure threshold of around 60 dB re 1  $\mu$ Pa (Fig. 3). Clupeiform fishes, e.g. herring (*Clupea harengus*), sprat (*Sprattus sprattus*) and sardine (*Sardina pilchardus*) have a small gas bubble tied closely to the utricle otolith, called prootic auditory bulla, enhancing their hearing abilities up to 3-4 kHz. However, a few species within the genus *Alosa* like the American shad (*Alosa sapidissima*) was shown to be able to detect sound up to 180 kHz (Mann *et al.*, 2001). Species that have a swim bladder, but lack any specialized morphologic structure to enhance their hearing sensitivity, e.g. cod (*Gadus morhua*), salmon (*Salmo salar*) or the European eel (*Anguilla anguilla*), are limited in sensitivity below 1 kHz and a sound pressure threshold between 75-100 dB re 1  $\mu$ Pa.

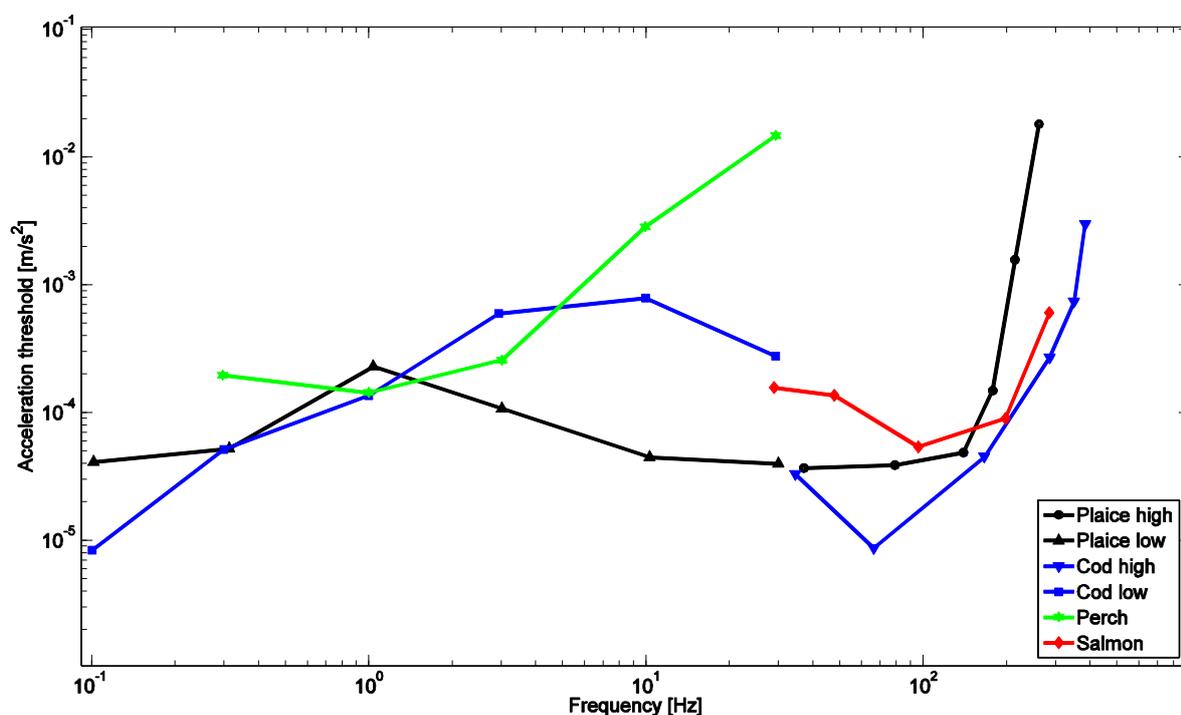
To summarize, the ability to detect sound pressure relies on the presence of a gas filled cavity that transforms pressure into motion. If there is a morphological structure connecting this cavity to the inner ear, higher sensitivity in terms of frequency and lower sound pressure threshold is achieved. This is exemplified in Fig. 5, where goldfish and herring show a low threshold and wider frequency sensitivity compared to salmon and eel. However, in those studies where the swim bladder was deflated no reduction in bandwidth sensitivity was noticed, only a decrease in sound pressure level (Offutt, 1974; Fletcher and Crawford, 2001). Realising that aquarium constitutes a complex acoustic environment, where the fish often is located close to a sound source in acoustical experiments, care has to be taken when interpreting results, especially when sound pressure and particle motion are not measured simultaneously (Craven *et al.*, 2009). The fish might have been responding to the particle motion and not the induced sound pressure level. This makes many published audiograms of hearing thresholds in fish questionable, as there is often a relative large discrepancy in hearing thresholds between studies of the same species (Popper and Fay, 2010).



**Figure 5.** Audiograms of several pressure sensitive species redrawn from published studies. Herring (● Enger, 1967), salmon (● Hawkins and Johnston, 1978), cod (● Chapman and Hawkins, 1973), European eel (● Jerkø *et al.*, 1989) and goldfish (● Fay, 1969).

Species without a swim bladder like benthic species (e.g. flatfishes, gobies and sculpins) and fast swimming pelagic species (e.g. tuna and mackerels) are only sensitive to particle motion (Sand and Karlsen, 2000). There is a relative similar sensitivity between species; of between  $10^{-4}$  to  $10^{-5}$   $\text{m/s}^2$  ranging from less than 1 Hz to about 300-400 Hz where after the sensitivity decreases rapidly (Enger *et al.*, 1993; Horodysky *et al.*, 2008). Both cod and plaice (*Pleuronectes platessa*) have been shown to be sensitive to frequencies as low as 0.1 Hz (Fig. 6). The discrepancy between the two audiograms of cod for 30 Hz, in Fig. 6, could be linked to difference in ambient noise level during the experiments as suggested by Sand and Karlsen (1986). Few species have been tested in terms of sensitivity to particle motion (Popper and Fay, 2010).

The dual sensitivity to sound pressure and particle motion in some species has not yet been explained in detail, but Chapman and Hawkins (1973) demonstrated in a field experiment measuring the hearing threshold for cod at different distances from a sound source that particle motion was the acoustic stimulus below 50 Hz and sound pressure above 50 Hz. Close to a sound source there is a steeper gradient in particle motion compared to sound pressure and the fish might use this gradient to discriminate between pressure and motion. A directionality hearing capability has been demonstrated in cod, improving sound detection (Chapman and Hawkins, 1973; Schuijf, 1975; Buwalda *et al.*, 1983). It seems that fish can use their sound detection ability in different ways depending on the stimulus. It can be speculated that their brain synthesizes the different signals to create a larger and complex picture.



**Figure 6.** Audiograms for several motion sensitive species redrawn from earlier studies. Plaice (● low <20 Hz, Karlsen, 1992a), plaice (● high >20 Hz, Chapman and Sand, 1974), perch (● Karlsen, 1992b), cod (● low <20 Hz, Sand and Karlsen, 1986), cod (● high >20 Hz, Chapman and Hawkins, 1973) and salmon (● Hawkins and Johnston, 1978).

## 4.2 Lateral line organ

Fishes can also detect motion in water is through the lateral line organ. This organ consists of several hundred or thousands neuromasts spread over the fish body. There are two types of neuromasts; canal neuromasts located within canals on the head and trunk, and superficial neuromasts that can occur in clusters or alone. The neuromasts are in direct contact with either the water or the canal fluids. Each neuromast has a cylindrical gelatinous cupola where sensory hair cells are embedded creating a mechanical coupling between the motions in the water or fluid and the sensory hair cells, similar to the otolith organs in the inner ear (Webb *et al.*, 2008). The neuromasts can register frequencies less than 1

Hz up to about 150 Hz and encode the duration, local direction, amplitude and phase of the hydrodynamic motion, resulting in a local pressure gradients over the body. Displacements of less than 1 nm are sufficient to cause a neural stimulation of the hair cells (Münz, 1989). The lateral line system is used for prey detection and predator avoidance in the near-field (up to a few body-lengths) as well as to help the fish to form a three-dimensional image of their local environment (Bleckmann, 2004). The limitation in detection distance of the lateral line and its role in hearing were shown by Karlsen and Sand (1987) and Karlsen (1992b) where acceleration thresholds of the inner ear were not affected when the lateral line system was blocked by the use of  $\text{Co}^{2+}$ , suggesting a limited role of the lateral line in far-field detection. This is most likely true for pelagic fishes but not for benthic species like sculpins and flatfish that lie directly on the seabed. A difference is that the sound can propagate through the seabed as well as the water and thereby increase the acoustic stimuli (Whang and Jansson, 1994). Braun and Coombs (2000) demonstrated an approximately equal detection range for the inner ear and the lateral line in prey detection in the mottled sculpin (*Cottus bairdi*). The diversity in morphologic structure of the lateral line organ is large and unique specializations to increase sensitivity exist. One example of this is the mechanical coupling (laterophysic connection) between the anterior part of the swim bladder and the lateral line in the skull of the genus *Chaetodon* (butterfly fishes) (Webb, 1998) thus significantly expanding the functional range of the mechanosensory lateral line system.

### 4.3 Sound localization

The ability to localize sound sources was demonstrated in fish with and without a swim bladder–inner ear connection (Chapman and Hawkins 1973; Schuijf and Buwalda, 1980). Cod was able to distinguish pure tones emitted alternately from two aligned sound projectors positioned at different distances, suggesting three-dimensional hearing capabilities (Schuijf and Hawkins, 1983). This ability is thought to be attributed to the inner ear as the sensory hair cells are organized into different orientation groups where each hair cell has one tall kinocilium located on one side followed by a subsequent row of more stiff stereovilli, from the tallest to the shortest. The mechanical stimulation of hair cells from the otolith creates a polarization over the surface and a directional sensitivity is achieved (Hudspeth and Corey, 1977).

Several studies investigated the directional sensitivity by replaying sound to fish at different angles and elevations (Chapman and Johnstone, 1974; Hawkins and Sand, 1977). However, the mechanism behind this ability is not yet known. As described earlier, the fish inner ear registers the directional particle motion of a sound wave. Notably, the fish should not be able to determine the direction of the sound based on particle motion as there is a 180 degrees ambiguity. There are some suggested theories to explain this ability, e.g. the phase model where the fish use the phase relation between the swim bladder and the inner ear to decide the direction (Schuijf, 1975). Kalmijn (1997) suggested that the fish swim in the direction of the particle motion, sensing the gradient. More recent studies, e.g. Rollo *et al.* 2007 and Zeddis *et al.* (2010), showed that fish adopt relatively quickly an orientation towards the sound's particle motion axis (if it is attracted to the sound). It is not only the inner ear that is used for sound localization as the lateral line also detects motion. The spatially distributed neuromasts of the lateral line system are better suited than the otolith organs to detect the gradient in motion in the near field as there will be a difference in fluid pressure between the canal pores within the canal segments along the body. As a consequence the lateral line will provide a greater spatial resolution of the acoustic field than the inner ear (Braun and Coombs, 2000) but only very close to the source. There are still many gaps in our understanding of how fish are able to locate a source. Could it be that the two systems, lateral line and otolith organs, are combined into one ability? Further, adding visual and olfactory cues would increase the environmental awareness even more.

### 4.4 Effects of anthropogenic noise on fish

Richardson (1995), described that, an animal's reaction to noise can be divided into zones of influence. This is a noise impact assessment commonly used for marine mammals, but it could also be applied to fish as it experiences the same range of effects (although the distances of each zone will be different). The author describes four zones representing areas where different disturbance effects or injuries could occur. These are; zone of hearing loss, injury or discomfort, zone of masking, zone of

responsiveness and zone of audibility, defined from the sound source and outwards. These zones have not any distinct borders and are species dependent.

#### **4.4.1 Zone of hearing loss, injury or discomfort**

When induced noise by humans in the sea becomes loud enough, fish are killed or sustain temporal (temporal threshold shift, TTS) or permanent (permanent threshold shift, PTS) hearing loss. This is because high intensity sounds like explosive blasts, impact pile driving or air-guns, can damage internal organs leading to death or damage of the sensory hair cells in the otolith organs (reviewed in Popper and Hastings, 2009). Unlike many other animals' fish adds hair cells to the inner ears through their life and also after being damaged by sound, as observed in goldfish by Smith *et al.* (2006). However, the result has only been replicated a few times and a contradictory result where no regeneration of hair cells was observed by McCauley and colleges (2003). More studies are therefore needed not only due to the contradictory results, but also due to the great diversity in fish ear morphology and physiology. If the hearing loss is only temporal, the fish will recover within hours or days (Amoser and Ladich, 2003). The recovery time depends on both duration and the frequency of the noise (Scholik and Yan, 2001). High enough levels to cause physical damage are thought to occur only relatively close to a pile driving operation or close to airguns in a seismic survey (Popper and Hastings, 2009). However, during the recovery time of the TTS the fish might be exposed to higher predation or be inhibited to perform biologically important activities.

#### **4.4.2 Zone of masking**

A fish will detect a signal if it is above ambient noise in terms of strength and within the hearing range. Farther away from a high intensity noise source or closer to a moderate source such as operating wind farm noise and shipping noise, masking effects on fish communication and other signals such as prey sounds or abiotic sounds could occur. The induced noise raises the ambient level making the detection of sound more difficult as the signal-to-noise ratio decreases leading to a reduction in signal detection distance. This occurs only if there is an overlap in frequencies between the induced noise and the sound of interest. For example, boat noise was observed to mask communication of several species of fish (Vasconcelos *et al.*, 2007; Codarin *et al.*, 2009). Fish has auditory filters covering several frequencies, called the critical bandwidth, making an average sound level over that bandwidth. The critical bandwidth was determined for goldfish (Enger, 1973) and cod (Hawkins and Chapman, 1975) and similar functions were demonstrated in other vertebrates (Fay, 1988). This makes it easier for the fish to detect a narrowband signal in an acoustic environment characterized by broadband noise, which is the normal acoustical state of the sea. In a comparison between anthropogenic noise and hearing in marine animals, averaging is necessary and often 1/3-octave is used when integrating over bandwidths (Wahlberg and Westerberg, 2005, Madsen *et al.*, 2006). Fish produces sound during courtship behaviour (Hawkins and Amorim, 2000), when feeding (Amorim *et al.*, 2004) and in antagonistic interaction (Vester *et al.*, 2004). Disturbances to these interactions could have severe implications on both individual and population level (Slabberkoorn *et al.*, 2010). It should be underlined that several species, e.g. cod (Brawn, 1961) and the plainfin midshipman (Brantley *et al.*, 1994) relies on acoustic signalling during courtship. A skewed sexual selection compared to the natural situation might be the result if the acoustic signalling becomes less important as size of drumming muscles and reproduction success is correlated (Rowe and Hutchings, 2004; Rowe *et al.*, 2008).

#### **4.4.3 Zone of responsiveness**

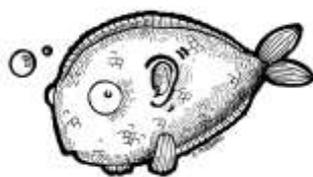
Farther away from a sound source fish might be disturbed by the noise resulting in a behaviour or physiological reaction. Behavioural responses can range from startle and avoidance responses to more subtle reactions such as changes in swimming activity, vertical distribution and schooling behaviour. Studies by Engås *et al.* (1996) and Engås and Løkkeborg (2002) reported a significant decline in catch rate in cod and haddock (*Melanogrammus aeglefinus*) after a seismic survey. This lasted several days after sound exposure was stopped. Further, new fish-survey and research vessels are being built or rebuilt to minimize the engine- and propeller-generated noise in order to minimize behavioural effects on fish (Skaret *et al.*, 2006; De Robertis *et al.*, 2010). Further, there are international standards for underwater-noise emission by research vessels issued by ICES (International Council for the

Exploration of the Sea) (Mitson, 1995). The response in fish to a noise disturbance is related to their habitat preference as pelagic species are more likely to swim away while benthic species will stay to a higher degree (Wardle *et al.*, 2001; Løkkeborg *et al.*, 2011). Habituation (decreased response to repeated stimuli) or sensitisation (increased response to repeated stimuli) to the noise could occur and are a temporal change in an animal's individual tolerance (Bejder *et al.*, 2009). Thus, the alternative of staying or leaving a noisy area will depend on the individual's tolerance to a disturbance or if the animal has enough energy to change habitat (Nisbet, 2000; Beale and Monaghan, 2004). In addition, the area might be too important to leave if the habitat is vital for its survival in terms of feeding, spawning or shelter (Bejder *et al.*, 2009). Startle responses was noticed when fish were subjected to a sound stimulus in tanks (Andersson *et al.*, 2007b; Kastelein *et al.*, 2008) and in the sea (Wardle *et al.*, 2001). The startle response is seen by a "C-start", that is the primary behaviour used by fishes to avoid an attacking predator. During a C-start the fish rapidly turns away from the stimulus into a "C" shaped body bend, followed by a powerful tail stroke to the opposite side of the body which moves the fish away from the threat (Eaton *et al.*, 1977). It will be costly for the fish to respond in this way and could have negative effects on survival in a longer perspective.

#### **4.4.4 Zone of audibility**

The zone of audibility is linked to the individual species' hearing threshold and sensitivity. Masking is overcome when the signal-to-noise ratio is high enough for a fish to sense the sound, while if the ambient sound from wind, waves, rain and biological noise are higher than the induced anthropogenic noise, the fish will not hear it. As fish can detect a narrowband signal in broadband noise, the induced noise does not need to be higher over the whole bandwidth for it to be heard by the fish. Wind and waves adds considerable sound below 500 Hz and below 10 Hz the turbulence from waves in shallow water dominates the spectrum (Hildebrand, 2009). Most fish will detect sound below 1000 Hz and a few species up to several kHz as described earlier. Many human generated noise sources such as shipping, wind farms and pile driving generates sound below 1000 Hz, which fish can hear. If a fish remain in an area exposed to noise levels above hearing threshold, but not at a level that triggers a behavioural response, other indirect effects might occur. Noise was shown to induce higher levels of the stress hormone cortisol in fish when exposed to noise (Wysocki *et al.*, 2006), which could disrupt growth, maturation and reproductive success (Pickering, 1993; Small, 2004). A combination of several stressors on the fish ecosystem such as eutrophication and overfishing might together with noise trigger a response even if the noise alone is not high enough to act as a stressor (Deak, 2007; Wright *et al.*, 2007).

Even though numerous studies are published showing effects of noise on fish, there are knowledge gaps in our understanding of the effects of noise on fish especially in terms of behaviour and masking effects. Few studies have been conducted probably due to the difficulties in reproducing a natural acoustic environment in tanks and aquariums. The results of experiments in such conditions cannot be easily applied to the natural environment in the sea (Wysocki *et al.*, 2007; Craven *et al.*, 2009). One has to be careful when extrapolating between fish species due to the fact that even closely related species might have different hearing abilities and react to a noise stimulus in different ways and we do not know how age and sex affects hearing abilities. Moreover, one must also be cautious with any attempt to extrapolate results between different sources of noise because the characteristics of the sources (e.g. air guns, ships, pile driving, and wind farms) differ significantly from one another in terms of duration and spectral intensity.



## 5 CONCLUSIONS AND DISCUSSIONS OF RESULTS

We have increased our ocean activities over the last decades in terms of constructions, shipping, oil and gas exploration and extraction, as well as fisheries. It is vital to scrutinize their influence on the environment if we want to hand over a living sea enjoyable for future generations. Natural science has not been able to keep up with technical advances such as the development of offshore wind farms and as a result, the impact on the marine ecosystem is not yet fully known. There are areas where the scientific knowledge is too scarce (e.g. noise disturbance and reef effect) but fortunately we have a better understanding in some other areas (Wilhelmsson *et al.*, 2010; Slabbekoorn *et al.*, 2010).

This thesis will add new results and support earlier conclusion on the effects of offshore wind farms on the marine environment with a focus on fish and to some extent the invertebrate and algae assemblages' colonization of the foundations. Further, this thesis describes behavioural reactions of fish from pile driving noise, studies the underwater noise emitted during the operational phase (both particle motion and sound pressure) and discussed possible effects on fish.

### 5.1 Artificial reefs

#### 5.1.1 Epibenthic assemblage

Wind farm foundations are made of either concrete or steel and could be of different sizes and shape such as gravitation foundation, monopile or jacket. The aim of **PAPER I** was therefore to experimentally test the importance of material (steel and concrete) during the initial (one year) colonization of vertical structures. This study was followed by **PAPER II** that studies the fish and epibenthic assemblage on operational wind turbine foundations, seven years after construction. Although there are differences between the offshore wind turbine foundations used today the common factor they all share is that they add hard substrate to the water column previously occupied only by water and to the seabed. The structures change both large-scale water movement in the wind farm area (Broström, 2008) and create local turbulence and fluctuating water velocity around the cylindrical structure and protruding parts (Guichard *et al.*, 2001). The foundations presence in the water column increases the likelihood that fish and invertebrate larvae will encounter a suitable habitat for settlement (Neira, 2005). Time of submergence as well as distance to natural reefs will determine who the first colonizer will be as larval supply is linked to season and hydrological conditions (Connell, 2001; Anderson and Underwood, 1994; **PAPER I**). The foundation's surface material and heterogeneity will also influence the earlier colonizers of the surface as boundary layer flows are important factors for settling organism like for hydroids and algae that are more attracted to a rough concrete surface while species like barnacles and tube worms glue themselves more easily onto the smoother steel surface (Koehl, 2007; **PAPER I, II**). The presence of resident adults plays also an important role in facilitating colonization or inhibiting new arrivals (Dean and Hurd, 1980; **PAPER I**). This was exemplified in **PAPER I** where the tunicate *Ciona intestinalis* became a dominant organism on several pillars, inhibiting further colonization of the substrata. Filtering organisms located high up on the vertical foundation have an advantage compared to those at the seabed in terms of low sedimentation rate and a continuous supply of food, carried by the surrounding waters (Wilhelmsson and Malm, 2008; Maar *et al.*, 2009; **PAPER I, II**) (see examples of organisms in Fig. 7a). Large colonies of blue mussels (*Mytilus* spp.) have been noticed around the base of offshore foundations in the Baltic Sea and are thought to be the result of dislodgement of mussels from the vertical foundation, creating beneficial habits for fish and mobile invertebrates (Wilhelmsson *et al.*, 2006a; Maar *et al.*, 2009; **PAPER II**). The effect from the introduced foundation on the benthic assemblage is only local as already at 20 m distance the assemblage is similar to natural once (Wilhelmsson *et al.*, 2006a; Maar *et al.*, 2009; **PAPER II**). Blue mussels changes the local environment by excretion of ammonium, which can be used by fast growing macroalgae species such as filamentous red algae (Norling and Kaustsky, 2007; Maar *et al.*, 2009). This was, however, not noticed by Wilhelmsson *et al.* (2006a) as the coverage of red algae was positive correlated with the distance from the foundation. Somewhat higher coverage of red algae was noticed on the foundation in **PAPER II** compared to Wilhelmsson *et al.* (2006a) four years earlier. Red algae are slower colonizers than mussels and in later stage of

succession, red algae may increase as seen on a nearby lighthouse (50 years) (**PAPER II**) and bridge foundations (6-16 years) (Qvarfordt *et al.*, 2006) and other wind farms (Dong Energy *et al.*, 2006).

Nutrients in the water are trapped by the assemblage high up on the foundations and are later transported downward into the seabed below as organic debris in the form of live mussels and faecal matter. This may result in local areas of anoxia where oxygen is used up in the degradation process, as was found by Zettler and Pollehne (2006) in their field experiment. The same negative impact was also noticed (by the author of this thesis) in the wind farm area the year before the study in **PAPER II**, where a band (30 cm wide) of a sulphide oxidising bacteria (*Beggiatoa* sp.) were encircling the base of the wind turbine foundations. Why this was not found during the study in Paper II is probably due to the usually good water circulation of the area. The impact on the soft bottom community is otherwise low at some distance away from the construction (Wilhelmsson *et al.*, 2006a; Maar *et al.*, 2009; **PAPER II**). The epibenthic invertebrate and algae assemblages on the foundations will continue to develop over the years, but will not likely resemble natural hard bottom communities as there is a difference in age and structural complexity (Connell, 2001, Perkol-Finkel and Benayahu, 2007; Wilhelmsson and Malm, 2008; **PAPER I, II**).

The introduction of hard substrate may be considered negative in valuable areas without any natural occurrence of hard substratum as the consequence will be an increased level of biological diversity with species not previously present in the area (Dong Energy *et al.*, 2006, Wilhelmsson and Malm, 2008; Brodin and Andersson, 2009; **PAPER I**). On the other hand, increased biodiversity is sometimes regarded as positive, creating a favourable habitat for fish and mobile invertebrates. If the foundations are located in a hard bottom area, the effect will be much smaller compared to a soft bottom area. Around the base of the foundations, rock or gravel is often added as scour protection creating even more of a complex environment. This adds up to 2.5 times more new hard surface to the area than the destroyed natural bottom (Wilson and Elliott, 2009). Synthetic fronds may also be laid out as scour protection creating a complex habitat for fish and other organism. Foundations could also be modified to facilitate the reef effect for fish and crustaceans as seen for wave energy foundations and restoration of reefs (Sherman *et al.*, 2002; Langhamer and Wilhelmsson, 2009). However, the added new hard substrate habitat is relative small compare to the whole wind farm area. At the wind farm Nysted in Denmark, the 72 gravitation foundations was estimated to cover an area of about 45 000 m<sup>2</sup>, corresponding to 0.2% of the total area of the wind arm (Dong Energy *et al.*, 2006). Nevertheless, with the expansion of more than 30 000 offshore wind turbines during the next 20 years, there will be a significant increase of hard substrates in European coastal areas. Unfortunately, most monitoring programs of wind farms end after only a few years resulting in a low knowledge of the long-term effects.

### **5.1.2 Fish assemblage**

The hard substrate habitat created by the introduction of wind farm foundations and scour protection will be colonized within hours or days after construction by bottom-living and semi-pelagic fish species (Golani and Diamant, 1999; Wilhelmsson *et al.*, 2006b; **PAPER I**). It is fish from nearby reefs that are attracted to the structure itself. How long time the first colonisation by fish will take is related to time when the construction occurs (e.g. what month of the year) as many fish have seasonal cycles, especially in temperate and cold-water regions (Holbrook *et al.*, 1994). Once the epibenthic assemblage starts to develop, as described earlier, the newly created habitat can support other fish species with ecosystem function and services such as food, shelter and spawning opportunities (Wilhelmsson *et al.*, 2006a, b; Moreau *et al.*, 2008; **PAPER I, II**). Habitat characteristics such as water depth, complexity and hydrographical parameters like water temperature, turbidity and salinity are other determining factors for colonization of the foundations (Connell and Jones, 1991; Elliot and Dewailly, 1995; Charbonnel *et al.*, 2002; Magill and Sayer, 2002). Over time, more species will be found around the foundations including juveniles that use the habitat as nursery area. Especially bottom associated species like gobies, wrasses and eelpout was noticed by Wilhelmsson *et al.* (2006a) and observed in **PAPER I** and **II** to respond to the introduced structures. Different species will respond in various ways to the introduction of the foundations as fish in the area can aggregate from the nearby area, attracted by the habitat for feeding (e.g. black gobies (*Gobius niger*) in **PAPER II**)

(see Fig. 7b) or new production of individuals as the habitat functions as spawning and nursery area, thus resulting in an increased carrying capacity of the area (Bohnsack, 1989). Bottom associated species will respond faster than the pelagic species as it is the bottom habitat that has been altered and they often have a more rapid life cycle. Gobies, especially the two-spotted goby (*Gobiusculus flavescens*) were found in large densities around wind turbine foundations and its protruding parts, feeding on zooplankton (Wilhelmsson *et al.*, 2006a; **PAPER II**). Fish could benefit from the changed water movements and turbulence, as it would enhance encounter rates of plankton, thus increasing feeding (Rothschild and Osborn, 1988). However, whether or not turbulent water enhances feeding rate among planktivorous fish and fish larvae is debated and field observations and experiments show somewhat contradictory results (MacKenzie, 2000; Utne-Palm, 2004). Since gobies and most other species have pelagic larvae, it is difficult to say where the recorded two-spotted gobies in the three following papers come from; Wilhelmsson *et al.* (2006), **PAPER I** and **II**, since water currents could transport the larvae from far away (Caley *et al.*, 1996; Beldade *et al.* 2007). The fish larvae will encounter the foundations more easily than horizontal seabed as they protrude through the whole water column and the created assemblage on and around the foundation are suitable habitats for settlement (Wilhelmsson *et al.*, 2006a; **PAPER II**). However, the juveniles can only be regarded as new to the population if they would have died instead of settling on the foundations, thus proving new production difficult. The foundations will also function as spawning areas as mussel shells and macroalgae could be utilized as nest (Skolbekken and Utne-Palm, 2001). Additionally, gravid females were noticed around several foundations in **PAPER II**. Based on this knowledge and by viewing the overall seabed characteristics of the strait where the wind turbines are located, the large abundance of two-spotted gobies are suggested being the result of new production.

Species diversity will increase on the foundations, but will level off after some time and stay more constant, but could still vary over season, especially in temperate and cold waters (Golani and Diamant, 1999; Wilhelmsson *et al.*, 2006b; **PAPER I**). The dominant natural substrate character (e.g. soft bottom, rocky bottom, and seagrass or macroalgae meadows) of the construction area will determine the number of new species found on the introduced vertical hard surface and the added rocky scour protection (Walsh, 1985; Coll *et al.*, 1998). When placed on an already rocky dominant seabed, few new species will be added to the area but the increase in total habitat surface could sustain more individuals (**PAPER II**). In contrary, when placed on a soft bottom, most of the colonizing fish will be hard bottom associated fish increasing the diversity of the area (**PAPER I**).

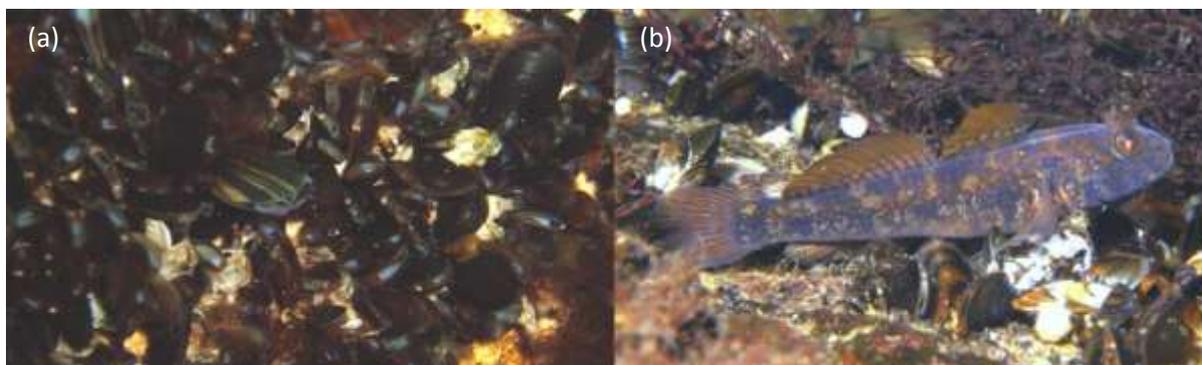
To summarize, fishes move to exploit resources, mainly food and shelter. Basically, fishes select foraging areas to maximize food intake and minimizing threats by available shelter. Fish that are only relocated to a smaller area and not replaced by new individuals as a consequence of, e.g. finite larval supply and limited food will not result in an overall population benefit, instead by aggregating towards a smaller area, the fish might be easier to catch by piscivorous fish or humans. Alternatively, new production is a more positive outcome, caused by new settlement of pelagic fish larvae that survives to spawn as adults, contributing with new individuals to the local population (**PAPER I, II**).

Pelagic species could be positively affected by the increased numbers of small benthic- and semi-pelagic fish in the wind farm area as food availability increases - but it takes time. To show that a wind farm has an effect on the fish population in a larger area, positive, negative or no effect is quite difficult and requires several years of monitoring to distinguish the effect of the wind farm from annual variations. Additionally, it takes several years for many species to become sexually mature and reproduce (e.g. for cod 2-4 years and for herring 3-5 years) and thus, contribute to the population in terms of new individuals. Commercial species like cod, eel, salmon, herring and several species of flatfish are subjected to intense fishing making it even more difficult to determine if any change in density was caused by the wind farm. The common methods used in monitoring effects of wind farms, e.g. echo sounders, otter and beam trawls, gillnet and fyke nets (see Fig. 2), sample only parts of the fish ecosystem and will only alert for a drastic change in fish community. Most results produced in the monitoring programs are difficult to find and are rarely published making it difficult to draw any conclusions of the effect on fish from the last decade's expansion of offshore wind farms. Those studies that are publically available (especially from wind farms in the UK and Denmark) have shown

no or little effect on fish abundance, but as describe earlier, most have been conducted only 2 to 3 years pre and post construction (see Dong Energy *et al.*, 2006; CEFAS, 2009). No programs have used visual census by scuba diver as was done by Wilhelmsson *et al.* (2006a) and in **PAPER II**. The relative small-scale effect on the fish community noticed in these two studies would not been observed in the other projects due to different sampling methods (Andersson *et al.*, 2007a). Even the longest monitoring program conducted to date, i.e. at the wind farm Lillgrund, in southern Sweden in the Öresund strait, showed no overall increase in fish numbers although redistribution towards the foundations within the wind farm area was noticed for some of species (i.e. cod, eel and eelpout) (L. Bergström, personal communication). Additionally, more species were recorded after construction than before; agreeing with the hypothesis that introduced hard bottom on a soft bottom area will increase the biodiversity locally.

Today, there is a limitation in technology and economy to build in waters deeper than about 30 m. One exception is the two demonstrator turbines built at 45 m depth in the EU supported DOWNVIInD project. If more seabed mounted or floating wind turbines are constructed in deeper waters, biological important shallow offshore banks could be spared and the contractors would receive less complains from coastal communities and tourist organizations.

There is a lack of management awareness and courage as stated by Petersen and Malm (2006) and Inger *et al.* (2009) in terms of decisions on where wind farms should be built and, dependent upon site, if they should be designed to either minimize negative the environmental impact or enhance the reef effect. Once a wind farm is built in an area with little biological importance, and if it is desirable, efforts should be made to increase the area's biological diversity by adding more artificial hard substrate than merely the foundations to create a living area and preferably make it a marine protective area (MPA). The MPAs need to be large enough to accomplish an effect on the fish ecosystem and it takes time (Côté *et al.*, 2001; Claudet *et al.*, 2008). When incorporated into modern fishery management, the refuge areas could contribute to commercial fisheries in small scale (Roberts *et al.*, 2005; Gaines *et al.*, 2010). There are however, other issues of possible disturbance to the fish ecosystem that need to be addressed such as effect from electromagnetic fields and noise and the latter will be dealt with in the next chapter.



**Figure 7.** (a) Blue mussels (*Mytilus* spp.) and barnacles (*Balanus improvises*), (b) black goby (*Gobius niger*) found on and around wind turbine foundations at Utgrunden wind farm. © Mathias H. Andersson.

## 5.2 Noise from offshore wind farms and impact on fish

### 5.2.1 The effect of construction noise on fish

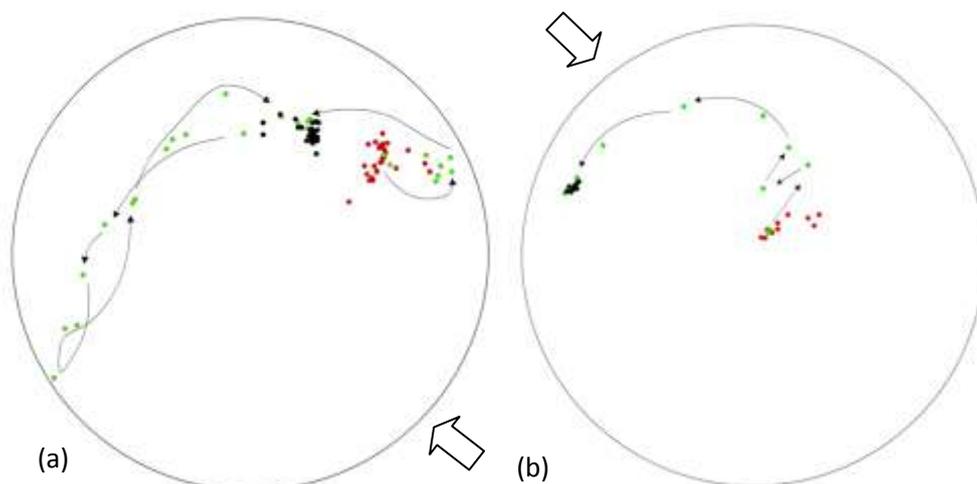
Presently pile driving is of major concern, especially in shallow waters (Erbe, 2009; Popper and Hastings, 2009). This method is the most commonly used in construction of offshore wind farms. For more details about pile driving noise, see chapter 3. Pile driving is the only anthropogenic non-blasting sound source that has killed and caused hearing damage in fish in the natural environment (see Popper and Hastings, 2009 and references therein). There have been few scientific studies of the effects of pile driving noise on the behaviour of fish as most are done by subcontractors to construction companies and not peer-reviewed (Popper and Hastings, 2009). Results from these studies vary, showing either strong or moderate effects or no effect at all. Further, fish cages used in many studies are small and might themselves affect the behaviour of the fish. Data are lacking not only on the immediate behavioural effects on fish close to a source, but also effects on fish further away from the source. **PAPER III** aimed to study the swimming behaviour in fish before, during and after 10 minutes of playback pile driving noise using an underwater loudspeaker in a semi-natural condition, i.e. 40 m wide mesocosm with natural seabed inside. This is the first study to demonstrate significant behavioural reactions in cod (*Gadus morhua*) and sole (*Solea solea*) to sound level's occurring up to 70 km away from a piling event. This result shows that the zone of impact on fish with relative good hearing (cod) is considerable large and that species lacking a swim bladder (sole) will react to the noise as well.

Playback was achieved using a J11 loudspeaker and the acoustical soundscape in the mesocosm was monitored as well as the movement of tagged fish. Both sound pressure and particle motion was measured where the latter component was measured using the sensor described in **PAPER IV**. The result showed a significant gradient in noise levels within the two mesocosm, allowing the fish to move from areas with different sound intensities. The piling noise used in **PAPER IV** was measured by Betke (2004) at a distance of 400 m. It can be assumed that the piling pulses from a piling event will change shape as a function of distance. However, spectral analyses show that most energy of the pulse is found below 1 kHz, thus the pulse is firsthand attenuated. The results of fish behaviour shown in **PAPER III** to pile driving noise are, therefore, valid at distances larger than 400 m. The study intended to find a threshold for behaviour reaction, but the results showed that there is a range in received levels where reactions occurred, both to sound pressure and to particle motion.

The typical behaviour of the cod was a significant initial “freezing response” at the onset of the piling noise followed by a period of increased swimming speed during noise exposure. When the noise was switched off the speed decreased again (more details in Mueller-Blenkle *et al.*, 2010; **PAPER V**). However, the variety in swimming speeds by individual cod during the playback period resulted in an overall non-significant effect. The reaction to the noise by cod is exemplified in Fig. 8a where the swimming pattern of one cod is shown. The trend of increased swimming speed was more profound in the near mesocosm experiencing higher levels of sound pressure and particle motion compare to the farther, indicating a behaviour threshold of between 153 and 133 dB re  $1\mu\text{Pa}_{(\text{peak})}$ . Cod showed a clear response to sound pressures between 156 and 142 dB re  $1\mu\text{Pa}_{(\text{peak})}$  and particle acceleration levels between  $6.5 \times 10^{-3}$  and  $8.6 \times 10^{-4} \text{ m/s}^2_{(\text{peak})}$  in the mesocosm closest to the loudspeaker. Only the radial component of particle acceleration in relation to the sound source is presented in **PAPER III**. In the far mesocosm, levels were measured to be 143 to 133 dB re  $1\mu\text{Pa}$  and  $6.6 \times 10^{-4}$  to  $4.1 \times 10^{-4} \text{ m/s}^2_{(\text{peak})}$  with less or no reactions. It is not straightforward to compare received levels with the ambient noise at the experimental site since the piling pulse is a transient and the ambient noise is a continuous sound (Madsen, 2005). **PAPER III** shows higher ambient sound pressure levels than **PAPER V** even though **PAPER III** was conducted in an area with low anthropogenic disturbances. This could be attributed to low-frequency noise emanating from the mesocosm structure and mooring chains.

As discussed earlier, few behavioural studies on piling noise exist or have been subjected to any peer-review process. However, other high-energy acoustic sources such as seismic surveys were shown to cause a significant decline in catch rate in cod and haddock (*Melanogrammus aeglefinus*) that lasted several days after sound exposure was stopped (Engås *et al.*, 1996; Engås and Løkkeborg, 2002).

Skalski *et al.* (1992) reports on similar results where reduced catch of rockfish was observed (*Sebaste* spp.) when exposed to air-gun noise. Pearson *et al.* (1992) showed that the rock fish reacted to the air-gun noise by either changing depth and/or increasing or decreasing swimming speed. They concluded that threshold for the more acute responses was 180 dB re 1 $\mu$ Pa, but subtle reactions could occur already at 161 dB re 1 $\mu$ Pa. The latter threshold is in line with the results of **PAPER III**. Variations in responses to sound between and within fish species were also shown by Andersson *et al.* (2007b) and Nedwell *et al.* (2007) and are linked to animal's individual tolerance to a stimulus.



**Figure 8.** Example of behaviour reaction from (a) cod and (b) sole when exposed to pile driving noise in large (40 m) cages (**PAPER III**). ● Red dots: movement before sound playback, ● green dots: movement during sound playback, ● black dots: movements after sound playback. The arrows outside the circles indicate the direction of the sound source. Both fish were in the cage closest to the loudspeaker. Figure redrawn from Muller-Blenke *et al.* (2010).

Sole showed a significant reaction in terms of increased swimming speed during playback at levels between  $6.5 \times 10^{-3}$  to  $4.1 \times 10^{-4}$   $\text{m/s}^2_{(\text{peak})}$ . Notably sole does not sense sound pressure; only the particle motion component of the noise. Thus, defining threshold for sole in terms of sound pressure is erroneous. Fig. 8b shows an example of reaction by one sole to the noise. The sound levels in **PAPER III** were lower than sound produced in front of inlets to power plants and constructions in lakes and rivers that were observed to induce escape reactions in several fish species (Knudsen *et al.* 1992; Sand *et al.* 2000; Sonny *et al.* 2006), thus, illustrating the variation in behavioural thresholds between species.

The loudspeaker was suspended 2.5 m above the seafloor and reactions in sole were not expected to occur. Sole and other flatfish lie on the seabed relying on their camouflage to hide them from predators and they are also known to be more active during the night (Kruuk, 1963). Gibson (1975) observed that plaice spent only 6% of their time swimming. The reactions noticed for sole in **PAPER III** are significant, showing that the sole were disturbed. By leaving the well camouflage position on the seabed the sole will be subjected to a higher risk of predation. Lagardère *et al.* (1994) demonstrated that sole reacts to wind induced noise although this was not observed in **PAPER III**. Field measurements of particle motion during piling are not available today, making conclusions of the zone of impact for sole unanswered. However, benthic species like the sole might be subjected to significant levels of pile driving noise far away from the actual operation as particle motion is transported through the sediment and radiates back into the water column, as speculated by Hawkins (2009).

There was some indication of a horizontal directional response away from the noise source by both cod and sole when they experienced the noise for the first time (Mueller-Blenkle *et al.*, 2010). There might have been other avoidance response not possible to detect with the present experimental set-up, such as a vertical movement as described by Pearson *et al.* (1992). Fish use particle motion for source

localization (see section 4.3) and the measured levels of particle acceleration were substantially higher than the ambient motion, suggesting that both cod and sole could sense the direction of the noise source. The change in overall swimming speed was less pronounced after the fish was exposed to repeated exposures. These results could be explained by habituation, i.e. increased tolerance threshold to the repeated noise. However, the effect was only noticed on an individual level, data do not support an overall conclusion. It should be underlined that habituation is not necessarily a preferred effect as there are costs involved as well (see Bejder *et al.*, 2009).

The sole in **PAPER III** was caught in the wild using trawl while the cod was farmed at the nearby hatchery. Ambient noise in the rearing tanks where the cod was held most of their life prior to the experiments and in the temporal holding tanks for sole was relatively low and similar in sound level to the ambient noise at the experimental site. As a consequence, the observed reactions in the experiments give a clear indication that the fish was disturbed by the noise. Owing to the known acoustic history for the cod, the results obtained are assumed to be valid to wild cod.

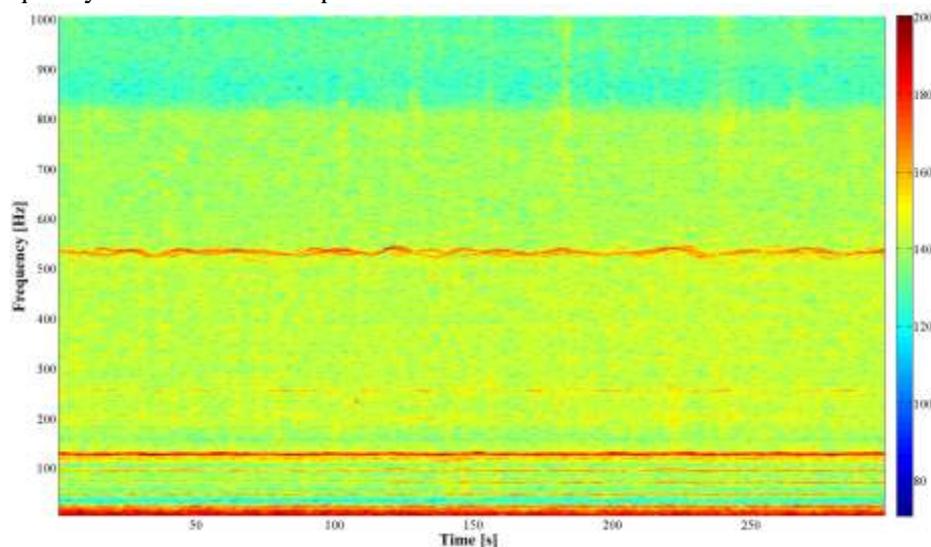
At the moment, there are no interim criteria for the onset of behaviour reactions or injury to fish from pile driving, similar to the criteria used for marine mammals (Southall *et al.*, 2007). However, Popper and co-authors (2006) wrote a white paper suggesting interim criteria based on the present knowledge of effects from piling and air-guns acknowledging that a direct comparison between those two noise sources is less than optimal. They proposed that interim criteria to be set at an SEL level of 187 dB re  $1\mu\text{Pa}^2\cdot\text{s}$  and a peak sound pressure level of 208 dB re  $1\mu\text{Pa}$  for any single strike. There are several studies in progress that are investigating the physiological effects from pile driving and ways to estimate and implement SEL into regulations (see for example Ainslie *et al.*, 2011; Erbe, 2011; Halvorsen *et al.*, 2011; Rodkin *et al.*, 2011). There has been no attempt to suggest interim criteria for particle motion due to the lack of investigations studying this phenomenon. The same status applies to the work on determining thresholds for behaviour reaction to transient sounds, although it is commonly cited as an exceedingly important task.

There are ways to decrease the noise produced during pile driving by using mitigations, such as bubble curtains, soft-start, ramp-up procedure, the use of deterrence devices or by enclosing the ramming pile with acoustically isolated material (for further details see Thomsen *et al.*, 2006; OSPAR, 2006). Soft start and ramp-up intend to scare away fish and marine mammals before the noise reaches damaging levels. These activities will decrease the zone of impact although levels are still loud enough to cause significant hearing damage in fish or behavioural reaction as observed in **PAPER III** (Popper and Hastings, 2009). The construction of most wind farms today are often only allowed during certain month when there is no spawning activity to prevent any impact. Still, avoidance from important commercial imported fishing grounds might occur all year around. More studies are needed on the impact from pile driving and other loud anthropogenic sources like air-guns involving measurements of particle motion to prevent negative impact on fish. There are other potentially indirect effects from piling noise such as masking or stress and this is discussed in the next section.

### 5.2.2 Offshore wind farm production noise and effects on fish

Concerns about the effects offshore wind farm induced noise is not only restricted to construction noise. The high intensity sound produced during piling is short-term while the noise produced during operation are long-term, more than 20 years (Wahlberg and Westerberg, 2005; Popper and Hastings, 2009). Knowledge of the characteristics of operational noise and the cumulative effect from several turbines is needed and have been on the wish-list for a long time (Wahlberg and Westerberg, 2005; Madsen *et al.*, 2006; Kikuchi 2010; Slabbekoorn *et al.*, 2010). The aim of **PAPER IV** and **V** was therefore to increase the knowledge on the noise produced by offshore wind farms and relate the measured levels and characteristics to hearing thresholds of fish and evaluate possible negative effects.

The noise from wind turbines is generated by the gearbox and generator and transferred into the water and sediment through the tower and foundation (Lindell, 2003; Betke *et al.*, 2004; **PAPER IV**). The blade-generated noise (0.5 to 2 Hz) was found to be reflected by the water surface or masked by wind-induced sound (Lindell, 2003; **PAPER IV**). Sound pressure is measured by using commercial available hydrophones while particle motion sensors are still not available on the market. A novel particle motion sensor was developed by Peter Sigray and Tim Fristedt at the Department of Underwater Research, Swedish Defence Research Agency (FOI), by combining known theories with an innovative design (**PAPER IV**). The sensor makes use of three seismic accelerometers situated orthogonally to each other inside a plastic sphere. The sphere was made neutrally buoyant to co-oscillate with the external sound. This sensor has a robust design allowing it to be deployed in long-term measurements in the sea (see Fig. 3a), which is not the case for the existing sensors (McConnell and Jensen, 2006; Kim *et al.*, 2008). Measured particle acceleration levels presented in **PAPER III** and **IV** are only expressed in terms of the radial component (x-axis) in relation to the sound source, i.e. the loudspeaker and monopile foundation. To show that the measured underwater noise was generated by the turbines, data from 3-axis accelerometers mounted either on the foundation or the gearbox were compared to measured noise from the underwater sensors (see Fig. 3b, c). The spectral characteristics of the noise generated by a wind turbine on a steel monopile (Utgrunden wind farm, **PAPER IV**) and a turbine on a concrete gravitation foundation (Lillgrund wind farm, **PAPER V**) were similar, showing a broadband character with a few dominating tones (Fig. 9). Both types of turbines generated tones below 600 Hz with one dominant tone between 100 to 200 Hz. These results agree with other measurements of operational noise (see comparisons and cited reports in Wahlberg and Westerberg, 2005; Madsen *et al.*, 2006 and measurements in Tougaard and Damsgaard-Henriksen 2009). When the wind is steady, the tones are stable and found inside a narrow band. During changing wind speeds and gusts the tones slides up and down apparently spreading the energy over a frequency interval (**PAPER IV, V**) (Fig. 9). Hence, to accurately estimate the acoustical energy of the tones, integration over a specified frequency window has to be performed.



**Figure 9.** Spectrogram of 5-min recorded operational noise 160 m from a turbine at the Lillgrund wind farm. The tonal components are clearly visible below 1 kHz with 127 Hz being the strongest tone. The sliding effect is clearly visible for 533 Hz tone. The colour bar to the right shows the sound pressure in dB re 1  $\mu$ Pa.

To estimate the total acoustic energy input to the ocean from a wind farm the energy of the entire spectrum is integrated (**PAPER IV, V**). However, fish has auditory filters called critical band filters (see section 4.4.2) that make detection of tones possible in an otherwise noisy environment. By integrating over different frequency windows, the intensity of the individual tones can be estimated when comparing the noise with hearing threshold from fish and other marine animals.

There are considerable discrepancies in wind farm source levels presented from various measurements most likely owing to differences in recording conditions, size and shape of the foundation, age and model of turbine. Most recordings were also performed at different distances to the turbines making comparisons difficult as transmission loss is site specific. The number of turbines in a wind farm will also contribute to the received noise level at different distances (**PAPER V**). The contribution from all the turbines in a wind farm (consisting of 48 turbines) was calculated to be 7 dB larger than the sound generated by one turbine (**PAPER V**). Source level and received levels were determined for several distances and production levels by developing a numerical model, validated by field measurements (see Table I, **PAPER V**). However, estimations of the source levels from other wind farms for the tonal components (from 25 to 180 Hz) were found to be between 150 to 120 dB re  $1\mu\text{Pa}_{(\text{RMS})}$  (Wahlberg and Westerberg, 2005; Tougaard and Damsgaard-Henriksen, 2009). The source level<sub>(1m)</sub> at Lillgrund are within that range; 136 to 132 dB re  $1\mu\text{Pa}_{(\text{RMS})}$  for the 127 Hz tonal component during 60 % and 100% power efficiency (**PAPER V**). These sound levels are produced 30 % of the time during the years 2008 and 2009, based on wind and power data. There are no studies to date to compare the measured source level of particle motion obtained in **PAPER IV**. The highest noise levels were recorded at 1 m distance from the foundation during moderate wind speeds ( $1.2 \times 10^{-2}$  to  $9 \times 10^{-3}$  to  $\text{m/s}^2_{(\text{RMS})}$  for the strongest tones) whereas Lindell (2003) recorded the highest sound pressure at high wind speeds as discussed in **PAPER V**. However, this difference could be explained by the change of gearboxes of the Utgrunden turbines that was done between the two measurements (cf. Lindell (2003) and **PAPER IV**).

Once the source level is calculated, a zone of audibility can be estimated for different species by comparing with known audiograms. Both the transmission loss for the area and ambient sound has to be known since they will affect the estimation. The Öresund strait is a noisy area with intense shipping. Nevertheless, the dominant tonal component of the wind farm noise (127 Hz) will pierce the ambient noise and make the wind farm detectable by fish at significant distances (**PAPER V**). Species like eel and salmon having poor sensitivity to sound pressure will only detect a wind farm like Lillgrund (during maximum production, wind speeds of 14 to 12 m/s) at a distance less than 1 km (based on a detection threshold of 0 dB). Fish with higher sensitivity of sound pressure, e.g. herring and cod, might detect the wind farm at a distance greater than 16 km. At this distance, the ambient noise of the strait will mask out the wind farm noise (**PAPER V**). These results are in line with other estimations of detection distance for the species presented above (Wahlberg and Westerberg, 2005; Thomsen *et al.*, 2006). All these estimations are associated with uncertainties since they are based on the assumption that all fish within a species have the same hearing threshold, which is not true as there are individual differences in sound detection (see references in **PAPER V** for the audiograms used in above estimations and Popper and Fay, 2010). In an area with different acoustical properties; the detection distances can be either shorter or greater. One can further assume that the signal detection is achieved at different signal-to-noise ratios (Chapman and Hawkins, 1973; Popper and Fay, 1973).

Fish lacking a swim bladder (e.g. gobies and flatfish) will only sense the measured particle acceleration at distance of about 10 meters from the foundation (Enger *et al.*, 1993; Horodysky *et al.*, 2009; **PAPER V**). Farther away, most species are limited by either their hearing threshold or the ambient sound masking the wind farm noise. The sensor measures the radial component of particle motion towards the sound source in the water and not levels on the seabed. The detection distance could therefore be greater for species laying in direct contact with the seabed as sound is not only induced to the water but also into the seabed as sound has even higher speed in the bottom than water.

The source levels presented in **PAPER III, IV and V** are not high enough to cause any injury on fish. They are, however, in the region of levels causing a behavioural reaction as observed in **PAPER III** although a direct comparison to **PAPER IV and V** is not possible to do due to the difference in acoustic properties. In close vicinity (less than 10 m) to a turbine the received level (about 119 to 136 dB re  $1\mu\text{Pa}_{\text{(RMS)}}$  for the 127 Hz component) are most likely sufficient to evoke a behavioural reaction in some species like cod. Westerberg (1994) noticed higher catch rates of cod and roach in the vicinity (100 m) of a turbine compared to farther away when the turbine was stopped (turbine source level<sub>(1m)</sub> was between 102 and 113 dB re  $1\mu\text{Pa}$ ), while tracked eels did not show any effect. In another study using tagged silver eels passing the Lillgrund wind farm performed in conjunction with **PAPER V**, no effect on swimming speed or direction were observed when eels were intercepting the wind farm (Andersson *et al.*, 2011). Owing to the resolution of the data, behavioural reactions similar to those studied in **PAPER III** were not possible to detect. Andersson *et al.* (2007b) demonstrated startle responses in three-spined sticklebacks and roach to playback of wind farm noise. The particle motion was not measured, thus making it difficult to draw any conclusion in terms of sound pressure threshold as the stimuli in the small tank was most likely particle motion. Other studies have shown that shipping noise causes avoidance reaction in fish such as changing depth or swimming speed (Mitson, 1995; Vabø *et al.*, 2002; Draščík and Kubečka, 2005 and section 4.4.3). Mitson (1995) reported further that cod reacted to shipping noise with a signal-to-noise ratio about 30 dB. Similar reaction threshold was estimated for cod, juvenile and adults, when exposed to single tones in the frequency interval 25-250 Hz in order to test habitat preferences (Müller, 2007). However, no measurement of particle motion was performed in the tank, limiting the validity of the conclusions. There are no consensus in appropriate threshold values for behavioural reactions in fish although Nedwell *et al.* (2003; 2006) proposed that sound pressure levels of 90 dB above the hearing threshold in fish could lead to significant avoidance reactions, and more subtle behavioural reactions at 75 dB. However, as **PAPER III** and other cited studies have shown, strong behaviour reactions could occur at much lower threshold and that the signal-to-noise ratios are a better descriptor since it is related to ambient noise. There are a few studies on behavioural thresholds in terms of particle motion. Studies using a sound projector producing low frequency tones (less than 20 Hz) to test avoidance reactions on juvenile salmon, eel and roach showed reaction thresholds of between  $10^{-2}$  and  $10^{-3}$  m/s<sup>2</sup> (Knudsen *et al.*, 1992; Sand *et al.*, 2000; Karlsen *et al.*, 2004; Sonny *et al.* 2006). These levels corroborate with observations measured levels close (less than 10 m) to a wind turbine foundation (**PAPER IV**).

Fish will most likely respond in different ways to various noise sources. The tolerance thresholds are linked to age, sex, condition, season and habitat preferences (Hawkins, 1993; Mitson, 2000; Popper *et al.*, 2004). Fish may respond spontaneously to sound by changing their behaviour or showing a startle reaction. Fish may habituate over time to repeated sounds with the results that it becomes difficult to evaluate effects of noise in laboratories and then applying the results to the natural situation. However, it is not certain that all fish will swim away from an area even with high noise disturbance since there is an individual tolerance level to a disturbance among animals (Beale and Monaghan, 2004). The choice of staying or leaving will depend on this tolerance and if the animal has enough energy to change habitat. An animal might also stay if the habitat is vital for its survival in terms of feeding, spawning or sheltering (Bejder *et al.*, 2009). Noise has been shown to induce higher levels of the stress hormone cortisol in fish, which could disrupt growth, maturation and reproductive success (Pickering, 1993; Small, 2004). Davidson *et al.*, (2009) demonstrated slower growth rate in rainbow trout (*Oncorhynchus mykiss*) during the first month of high noise exposure in an aquarium experiment, but no overall discrepancy between high (149 dB re  $1\mu\text{Pa}_{\text{(RMS)}}$ ) and low (117 dB re  $1\mu\text{Pa}_{\text{(RMS)}}$ ) treatments after six months. Slow initial growth rate were also noticed for caged carp close to a drilling operation (Sun *et al.*, 2001). Nonetheless, fish in the two experiments recovered after some time. Being small could increase the risk to be eaten by predators and is, therefore, a significant negative effect of noise. The effect of noise on fish egg and larval development are limited and results are somewhat contradicting (reviewed in Popper and Hastings, 2009). However, eggs and to some extent larvae cannot swim away when exposed to high levels of noise and are, therefore, more vulnerable than adult fish.

Many fishes use sound during spawning, locating mates and antagonistic interaction (Hawkins, 1993; Bass and Ladich, 2008; Kasumyan, 2008; Rowe *et al.*, 2008). Noise from a wind farm increases the ambient noise in the area (**PAPER IV, V**) making the detection of these sounds more difficult as the signal-to-noise ratio decreases; a phenomenon called masking, see also section 4.4.2. It occurs only if there is an overlap in frequencies between the induced noise and the sound of interest. For example, boat noise was shown to potentially mask communication of several species of fish (Vasconcelos *et al.*, 2007; Codarin *et al.*, 2009). Masking of spawning and antagonistic signalling might occur close to the foundations where the received noise levels are highest. Gadoid fish can produce grunts at source levels<sub>(1m)</sub> of 120–133 dB re 1 µPa (Hawkins and Rasmussen, 1978; Nordeide and Kjellsby, 1999; Wahlberg and Westerberg 2005), which corresponds to a level of wind farm noise found at a distance less than 10 m from the foundation (**PAPER V**). Wahlberg and Westerberg (2005) estimated that the detection distance of sound produced by haddock would be reduced due to masking from a wind farm, although still detectable at a distance of 4 m. Most interactions such as spawning sounds occur at short distances (Brawn, 1961; Amorim and Neves, 2008) where both sound pressure and particle motion are relevant stimulus. Thus, fishes are most likely able to detect communicative sounds with all their acoustical senses, including the lateral line organ (Lugli and Fine, 2007).

Sound pressure levels in water cannot directly be compared to sound levels in air as they are defined using different reference values, due to the fact that water has higher density than air (1 µPa in water and 20 µPa in air). Still this is often done when attempts are made to make acoustical data accessible for journalists, legislators and the public. It is relative simple to mathematically recalculate the sound levels, but it should be underlined that marine organism receiving sound in the water has a different set of hearing organs compared to humans. The comparison between sound sources measured in different medium will only be hypothetical and should therefore be avoided (Finfer *et al.*, 2008).

In summary, owing to the restricted knowledge of sound detection in fish and the limitation in sound pressure estimations, fish without a swim bladder or other sound pressure detector, e.g. sculpins, gobies and flatfish will only perceive offshore wind farm noise close (less than 10 m) to the foundation generated during maximum power production. Fishes with a swim bladder sensitive to sound pressure although not having any enhanced hearing ability, e.g. salmon, trout (*Salmo trutta*), eel, perch (*Perca fluviatilis*), and pike perch (*Stizostedion lucioperca*) will possibly detect the noise up to 1 km distance. Species having better hearing than previously mention species, e.g. cod, haddock (*Melanogrammus aeglefinus*) and herring could detect the wind farm at a distance of several kilometres up to tens of kilometres. Finally, species with a specialization to enhance pressure detection (i.e. Weberian ossicles) like carp, roach (*Rutilus rutilus*) and goldfish (however goldfish in not that common the Baltic Sea or the Öresund strait) can detect the wind farm at more than 20 km distance. Although the last two groups of fish will most likely perceive the wind farm at much less distance as the ambient noise masks the wind farm noise within 16 km distance. The long detection ranges are caused by the tonal components of the wind farm noise piercing the ambient noise as well as the “park effect” raising the induced noise levels with another 7 dB. If these tones are removed, the possible impact on fish and other marine organisms will likely decrease, including possible behavioural reactions. With new technology that already is available for wind turbines on land (i.e. direct drive of the gearbox) and by implementing the knowledge of fish hearing, the impact from offshore wind farm generated noise could be drastically reduced.

## EPILOGUE

What about attraction due to reef effect or avoidance due to noise? My first notion of a possible noise disturbance to fish from offshore wind farms came during a dive around a wind turbine performing a visual census of the fish ecosystem. It felt like my whole body vibrated when passing close to the foundation. The noise was also clearly audible by my ears at a considerable distance. However, fish were swimming care free, to my observation, in the loud noise. As this thesis has described, the introduction of offshore wind foundations will affect the local demersal fish ecosystem and possibly also free ranging pelagic species. An attraction effect has been confirmed by mine and other studies. An increase in overall biomass (i.e. new production) of fish has not been proven although some indication from this study and other artificial reef studies point in that direction. Still, it takes time for any significant effect to be observable due to natural variation. Apparently, some fish will live in close vicinity to these wind turbine foundations and also temporally spend time foraging around them. However, generated noise described in this thesis shows that moderate levels of broadband noise with strong tonal components, clearly audible for many fish, occurs at several kilometres away. It is only within a few meters of the foundations that the noise is at a level that could cause significant behavioural reactions as shown in aquaria and field studies. Whether or not the fish are adapting to the noise is difficult to prove scientifically, but if there are indirect effects these could affect the local population. The answer to the stated question is that the question is wrongly formulated, the issue is more complex. My suggestion is that future studies should combine acoustic measurements with behavioural studies using acoustical tags to monitor fish movement within and outside the wind farm to evaluate the two effects.



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